TRANSACTIONS
OF THE
AMERICAN GEOPHYSICAL UNION

Volume 17

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Parts I and II

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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION
SEVENTEENTH ANNUAL MEETING

APRIL 30, MAY 1, 2, 1936
WASHINGTON, D. C.

WEST COAST MEETING
JANUARY 31 AND FEBRUARY 1, 1936
PASADENA, CALIFORNIA

PART I

REPORTS AND PAPERS, WASHINGTON, D. C.
GENERAL ASSEMBLY AND SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY, TERRESTRIAL MAGNETISM AND ELECTRICITY, OCEANOGRAPHY, AND VOLCANOLOGY

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1936

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now seven sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, and (g) Hydrology. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section; the Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology.

Annual assemblies of the Union and annual meetings of its sections for the discussion of reports and for symposia are held each year. The first thirteen assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C.; in 1933 and 1934, in addition to the annual general assemblies and meetings of each of the seven sections held in Washington, D. C., meetings of the Section of Hydrology were held at Berkeley, California. The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1929, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, and sixteenth annual meetings were published in June 1931, June 1932, June 1933, June 1934, and August 1935, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, also one of the miscellaneous publications of the Council, includes the transactions of the seventeenth annual meetings held at Washington, D. C., April 30 and May 1 and 2, 1936, and of the meeting of the Section of Hydrology at Pasadena, California, January 31 and February 1, 1936. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The scientific session of the General Assembly was devoted to a symposium on recent trends in geophysical research and included the following papers: The place of geodesy in geophysical research, by William Bowie; Recent developments in the geophysical study of oceanic basins, by R. M. Field; Trends in seismological research, by James B. Macelwane; Recent progress in the physical interpretation of synoptic weather-charts, by E. W. Woolard.

Reports were received from four special committees as follows: (1) On geophysical and geological study of oceanic basins; (2) on geophysical and geological study of continents; (3) on establishment of an American journal of geophysics; and (4) on consideration of desirability and feasibility of inviting the International Union of Geodesy and Geophysics to hold its seventh triennial general assembly in 1939 at Washington, D. C. The first three are published in this volume. The Executive Committee was empowered to further consider reports (3) and (4) and to take action as circumstances may warrant.

An interesting feature of the Assembly was the exhibits prepared by the special committee on the geophysical and geological study of continents. The central item was a relief model, constructed to scale, which showed the approximate configuration of the "basement-complex" rocks underlying that portion of the United States extending from the Atlantic seaboard to and just beyond the Rocky Mountain Front Ranges. With the irregular blanket of sedimentary rocks removed from the "basement" surface, the model made clear the nature, form, and interrelation of both the buried and emergent mountain ranges of this region. The relations of the ranges to the profound troughs which flank them, and to the more remote dome-shaped uplifts and basin-like depressions, were also thus disclosed.

In order to show how "basement-structure," as portrayed by the model and by its parent structure contour-map, also finds significant expression and reflection in the areal distribution of surface-sediments, in local variations in the force of gravity, in local variation in magnetic intensities, and in regional variations in earth temperature-conditions, maps and diagrams were also exhibited in proximity to the structural model as follows: (1) The United States Geological Survey's areal geologic map of the United States; (2) contour-map showing configuration of pre-Cambrian surface for portion of United States east of Nevada (prepared by R. G. Moss, formerly Eleanor Tatum Long Fellow of Cornell University and now with the Phillips Petroleum Company, and exhibited by courtesy of Mr. Moss and The Geological Society of America);

(3) contour-map showing configuration of surface basement-complex beneath portion of United States between Atlantic seaboard and Rocky Mountain Front (compiled by the special committee); (4) gravitational iso-anomaly contour-maps of the Eastern United States, Yellowstone-Black Hills, and West Indian regions (compiled for the special committee from United States Coast and Geodetic Survey data by George P. Woollard); (5) geothermal maps showing (a) local temperatures at depths of 5000 and 10,000 feet in United States and parts of Canada, (b) relation of structure to temperature in Salt Creek Oil Field, and (c) relation of temperature to buried topography in Eastern South Dakota (compiled for the special committee from publications by Darton, Van Orstrand, and Spicer by William S. McCabe); and (6) tectonical and geophysical map of Wichita-Arbuckle Region showing relations between geologic structure of a buried mountain-system and local variations in gravitational and magnetic forces (as published by A. van Weelden, World Petroleum Congress Proceedings, v. 1, p. 174, 1933).

The nine resolutions adopted, as published in this volume, included five on the deaths during the year of Arthur J. Weed, Roy Jed Colony, Edwin Jay Brown, Christian Huff, and Veryl R. Fuller. The other four resolutions concerned national progress in geophysics as follows: On topographic mapping, on Naval Observatory time-signals, on forms for recording oceanographic observations, and on extension of hydrographic surveys.

In the Section of Geodesy 11 papers and reports were presented. Six of these dealt with progress and development of geodetic operations and instruments in Canada, Central America, Mexico, and the United States; four related to gravimetric surveys, apparatus, and interpretations; one concerned features of the Hawaiian Island Arc.

The Section of Seismology held three sessions jointly with the Eastern Section of the Seismological Society of America. The 22 communications may be classified as follows: Theoretical interpretations and analysis, 8; individual earthquakes and seismic measurements, 4; research in engineering seismology and applications, 3; geology and deep-focus earthquakes, 2; seismic instruments and stations, 3; progress-report for the United States, 1; earthquake activity, 1.

The Section of Meteorology heard nine papers bearing on theoretical aspects (2), on long-range forecasting (3), on correlation of solar and meteorological phenomena and upper-air results (3), on eclipse-meteorology (1).

Thirteen communications were received by the Section of Terrestrial Magnetism and Electricity. These were concerned with instrumental matters (3), with magnetic correlations with cosmic radiation, radio transmission, and solar-activity phenomena (5), with magnetic anomalies (2), with electric exploration of the troposphere and stratosphere (1), with magnetic perturbations (1), with magnetic diurnal-variation (1). The Secretary, besides reporting progress on the British Admiralty's non-magnetic vessel Research, submitted brief summaries of progress-reports dealing with magnetic and electric researches by 11 organizations in Canada, Mexico, Peru, Western Australia, and the United States, including Alaska, Hawaii, and Puerto Rico.

Eleven communications at the meeting of the Section of Oceanography related to progress during the year of five governmental and private organizations doing oceanographic work. Four papers had to do with dynamical oceanography and ocean-currents. Two papers gave summaries of explorations of submarine canyons off California and between the Hudson Gorge and Chesapeake Bay.

The following nine papers were discussed at two sessions of the Section of Volcanology: The origin of lamprophyres; Slopes of the walls of lunar craters; the solubility of water in magma at high pressure; Two African nephelines; Volcanological boron compounds; Some recent studies of Sierra Nevada Pluton; Crystallization of granodiorite magma, Ouray District, Colorado; Origin of anorthosite in the Adirondacks and in general; Mode of intrusion of pre-Cambrian granites in central Boulder County, Colorado.

There were four sessions of the Section of Hydrology. The first two were devoted to 19 general papers--five on ground-water, two on stream-channel storage, six on surface-water and surface-runoff, one on glaciers, four on erosion and flood-control, one on evaporation. A symposium on ground-water--arranged by David G. Thompson--occupied all the third session and included 11 communications. At the fourth session the annual reports of the Section's nine permanent research committees were received and discussed; these are the committees on (1) snow, (2) glaciers, (3) evaporation, (4) absorption and transpiration, (5) rainfall and runoff, (6) physics of soil-moisture, (7) underground water, (8) dynamics of streams, (9) chemistry of natural waters.

At the Pacific Coast meeting of the Section of Hydrology, January 31 and February 1, 1936, held at the California Institute of Technology, there were three sessions of the Section and a fourth session was devoted to a joint meeting with the Western Interstate Snow Survey Conference. The first session of eight papers constituted a Symposium on contribution to ground-water supplies; at the second session--jointly with the Snow Survey Conference--eight papers related to coordination and standardizing of snow-surveying and its methods; eight communications at the third session discussed basic hydrologic data, forecasting, interrelations of hydrology with plant-growth, stream-flow, and evaporation; seven papers at the final session dealt with experimental and chemical aspects of hydrological investigations.

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of sections. The volume of Transactions herewith includes, either in full or in abstract, over 130 papers and reports presented during the seventeenth annual meeting at Washington and over 30 papers and reports presented during the meetings at Pasadena of the Section of Hydrology and of the Western Interstate Snow Survey Conference. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Carnegie Institution of Washington and from members of the Union, of the Western Interstate Snow Survey Conference, and of the Eastern Section of the Seismological Society of America. C. C. Ennis proofread the typed copy, and the authors, except for a few who could not be reached, also revised their matter as prepared for publication. The final copy was prepared by J. J. Capello, whose skill and constructive arrangement of the copy are evidenced in the excellent reproduction by the A. L. Sauls Planograph Company of Washington; he was assisted in this by W. N. Dove. Besides its obligation to authors, to members of committees, and to our colleagues in Canada, Mexico, and abroad, who contributed to the seventeenth annual meeting, the Union is indebted to W. C. Hendrix for preparing many drawings of which the originals submitted were not suited for planographic reproduction and to P. G. Ledig for photographic work.

The total membership of the Union May 1, 1936, was 768--a net gain of 156 during the past year. There is wide-spread interest in the coming seventh triennial assembly of the International Union of Geodesy and Geophysics to be held during September, 1936, at Edinburgh, Scotland. Thus far over 30 of our members have arranged to attend and have been designated as delegates--by far larger than any American delegation attending any previous general assembly of the International Union.

The increase in membership during the year and the notably wide geographic distribution of new members evidence continuing and increasing interest in geophysics. It is felt no small part of this enlarging appreciation of the value of geophysical research is to be credited to the publication and distribution of the Transactions of the Union. That the Transactions play important part, both practical and theoretical, in international coordination of American progress in earth physics is shown in favorable comments by geophysicists of many countries. It is to be hoped, therefore, that the publication of this yearly record of American progress in the geophysical sciences may be adequately maintained not only in the national interest but also because of its value in the stimulation, orientation, and coordination of international endeavor in these fields.

Jno. A. Fleming, General Secretary
American Geophysical Union

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AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

GENERAL ASSEMBLY

Washington, D. C.
May 1, 1936

Reports and papers

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REPORTS OF COMMITTEES

REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEANIC BASINS

R. M. Field, Chairman

D. C. Barton
W. Bowie
W. H. Bucher
M. Ewing
J. A. Fleming
C. A. Heiland
H. H. Hess
C. O. Iselin
Arthur Keith
J. B. Macelwane
H. A. Marmer
F. E. Matthes
R. S. Patton
F. P. Shepard
H. C. Stetson
W. H. Twenhofel
P. Weaver
F. E. Wright

The Chairman of this Committee has discussed this subject, in general, as part of the Symposium on the Recent Advances in Geophysics (see paper "Recent developments in the geophysical study of oceanic basins", later in these Transactions). This report is, therefore, confined to the specific work of the Committee since its last annual report.

During the past year the experiment in submarine seismic surveying (as proposed by our Committee) has been reasonably successful. Under the able leadership of Ewing, and with the important cooperation of Professor B. L. Miller, of Lehigh University, Captain N. H. Heck, Dr. H. B. Bigelow, and Columbus Iselin (and also the invaluable support of the Geological Society of America and the Woods Hole Oceanographic Institution), this new and important technique has been made available for structural studies of the submerged continental shelf. Because of exceedingly favorable weather-conditions in the late fall, we were also able to run a seismic profile from the edge of the Piedmont, near Norfolk, out to the continental margin, proving that along the line of this traverse the Pre-Cretaceous surface tilts continuously seaward, and is covered by two stratigraphic miles of late Mesozoic and Tertiary sediments. It is interesting to note that, as the eastern end of this traverse, the thickness of the Mesozoic-Cenozoic sediments is approximately equal to twice the height of the bathyal slope. It is now of the utmost importance to determine the thickness of the sedimentary prism beyond the bathyal slope. Your Committee is now working on the important technical problems associated with the use of the seismic method at 1000 to 1500 fathoms.

The plans proposed by your Committee in 1936 for a marine gravity-survey in the easterly and southerly West Indies are now practically completed. The Expedition will leave Panama on or about November 30, 1936, finishing at Philadelphia on or about the middle of January. The Expedition has been so planned as to permit the running of one or more gravity-profiles from the oceanic basins across the submerged continental shelf, after the West Indian survey has been completed. The principal objects of this Expedition are: (1) Determine the shape and direction of the foredeep; (2) complete the data as to the direction and extent of the strip of high negative anomalies whose western limit was determined by the previous Navy-Carnegie and Navy-Princeton expeditions; and (3) check and supplement the seismic profile previously described.

This Expedition will be under the direction of Captain L. R. Leahy, Hydrographer of the United States Navy. The civilian scientists who will operate the Vening Meinesz gravity-machine are: Dr. Maurice Ewing, of the Department of Physics, Lehigh University; Lieutenant A. J. Hoskinson, United States Coast and Geodetic Survey; and Dr. Harry Hess, Department of Geology, Princeton University. Your Committee is deeply indebted to Dr. F. Vening Meinesz for his supervision of the program and also for his invaluable help in calibrating the apparatus. Thanks are also due to Dr. H. U. Sverdrup, of the Geophysical Institute of Bergen, for the loan of the apparatus. Mention should also be made that your Committee is also receiving the advice and cooperation of Dr. F. B. Jewett and his staff, of the Bell Telephone Laboratories, in the development of an automatic timing device. It is expected that the addition of this device to the Vening Meinesz apparatus will greatly facilitate the determination of gravity at sea.

Your Committee feels that the time is at last "ripe" for a well-planned attack on the geology of submarine areas because of the recent perfection of the following geophysical techniques:

(1) Sounding and positioning--It is now possible by geophysical methods to make rapid and accurate maps of the bottoms of the oceans and seas (see report of Special Committee on Geophysical and Geological Study of Oceanic Basins for 1935, pp. 6-18 of Transactions of Sixteenth Annual Meeting).

(2) Gravity--Marine gravity-surveys have already produced important data as to the relative densities of the suboceanic lithosphere. Although these surveys require the use of a submarine, the United States Navy has and is continuing to cooperate in splendid fashion.

(3) Sampling--(a) Stetson has proved that dredges may be used effectively to collect lithologic samples and fossils from the sidewalls of submarine canyons; (b) Piggot has developed a core-sampler which can procure a number of feet of the top layers of submarine formations.

(4) Seismic--Ewing and Heck have adapted the seismic method to submarine geology with surprisingly effective results. It is important to note, therefore, that we are now assured of another geophysical method for testing and amplifying present and future marine gravity-data.

While it is highly probable that relatively independent and sporadic uses may be made of the above-named geophysical methods, it is highly essential, because of the size of the terrain, as well as the special areas to be explored, that a well-planned "institution" of operations should be set up to continuously carry on the geophysical and structural study of oceanic basins and marginal seas. As proposed above, a ship should be provided for this purpose, properly manned, officered, and operated under the technical supervision of an experienced agency, such as the Woods Hole Oceanographic Institution. It is also important that the scientific program of this ship should be supervised by a committee of geophysicists and geologists who have been carrying on this specific work from its inception, and who are familiar with the marine and geophysical, as well as the geological problems cited above. It is hoped that both the British and Russian governments may find it practical to enlarge the activities of their non-magnetic ships now building. The United States, however, has no such ship available or in prospect. Further, the operations of the United States Coast and Geodetic Survey are confined to the coastal waters of the United States, and it is hardly to be expected that ships of the United States Navy could do any more marine geophysical and geological exploration than they are doing at the present time. The same holds true for such a vessel as the *Atlantis*, of the Woods Hole Oceanographic Institution.

Your Committee, therefore, after careful consideration, urges that every possible means be employed to commission a special vessel for geophysical and geological work at sea, especially in waters contiguous to the United States.

In conclusion the Chairman wishes to call to the attention of all members of the American Geophysical Union that the geophysical and geological study of the structure of oceanic basins and their margins will be discussed at the meeting of the International Union of Geodesy and Geophysics in Edinburgh September 15-25. An international committee of geophysicists and geologists is now being formed to outline and open the discussion before the general assembly.

Princeton University,
Princeton, New Jersey

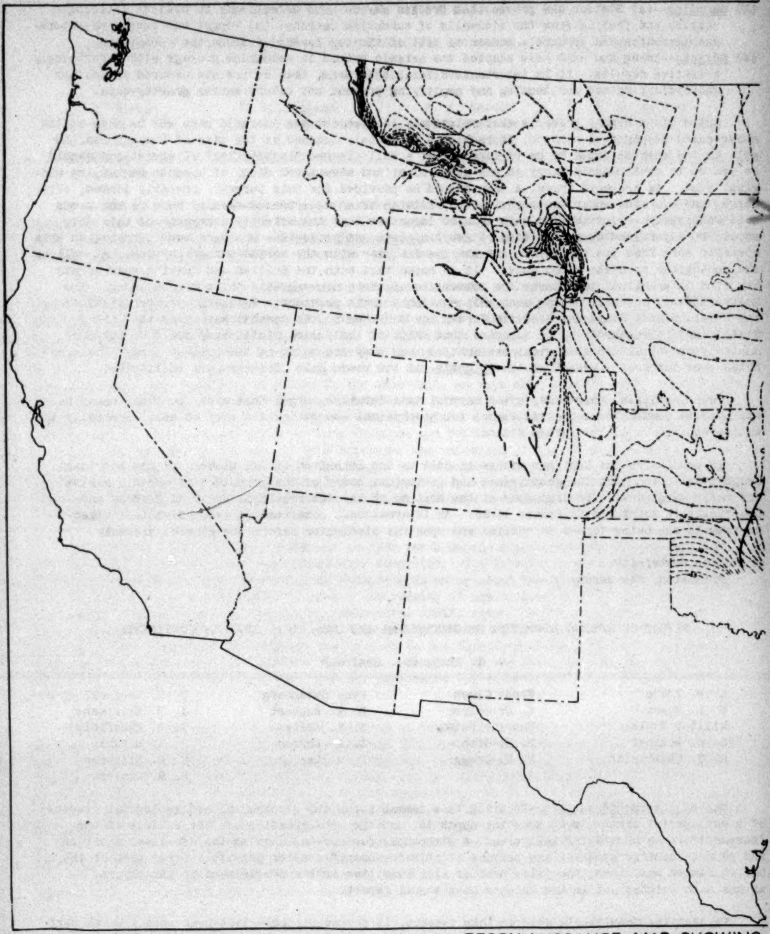
REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

W. T. Thom, Jr., Chairman

L. H. Adams
N. L. Bowen
William Bowie
G. C. Branner
R. T. Chamberlin
Ernst Cloos
E. De Golyer
Maurice Ewing
O. H. Gish
W. R. Gregg
Beno Gutenberg
M. K. Hubbert
S. F. Kelly
E. S. Larsen
F. W. Lee
C. R. Longwell
J. B. Macelwane
G. R. Mansfield
O. E. Meinzer
L. B. Slichter
H. R. Wanless

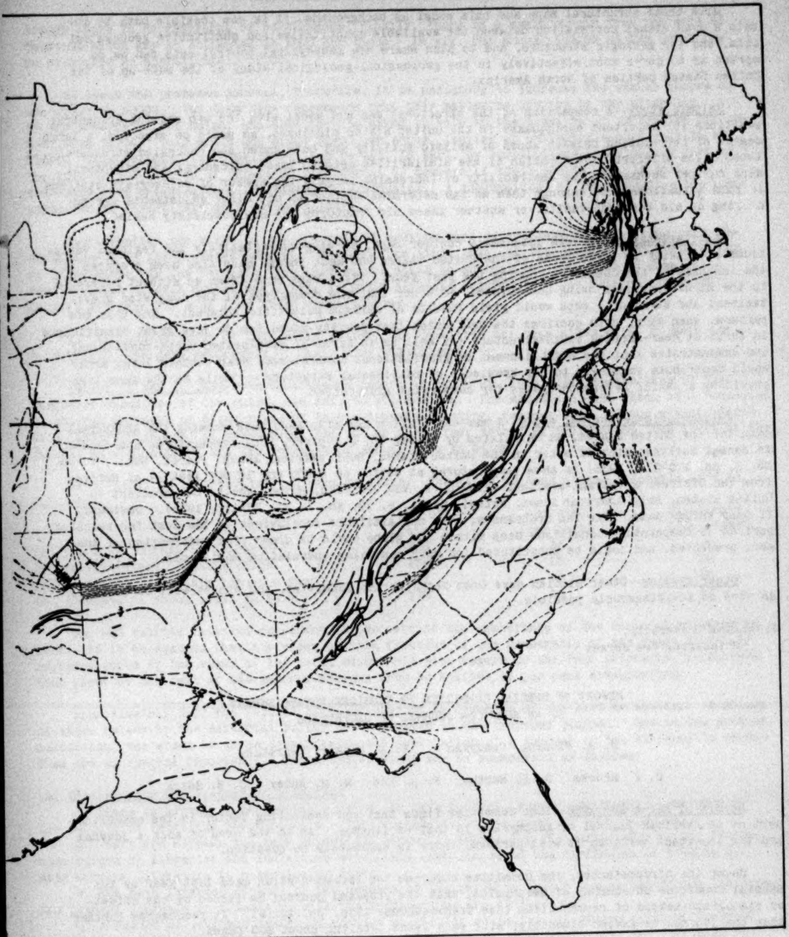
Map of "basement"-surface--To bring to a common focus the geophysical and geological studies of a continental area we must know the depth to, and the configuration of, the surface of the "basement"-rocks underlying that area. A structural contour-map showing the sea-level position and general configuration of the surface of this "basement"-complex beneath a large part of the United States was, then, the prime need of this Committee in the development of its program -- as was also pointed out in the Union's last annual report.

To meet the Committee's need in this respect, it seemed possible last year that a large part of the necessary work of compilation could be done by unemployed young scientists, under the relief appropriations which had just been made. This proved unfeasible, however, for several reasons, and the map-compilation was consequently pressed forward by the Committee -- with as broad cooperation as possible -- and with the results (1) that a preliminary map of the crystalline surface has been prepared on the scale of 1:2,500,000, and (2) a detailed atlas of 125 sheets is being prepared on the scale of 1:500,000. The first of these maps shows the general configuration of the surface of the basement-crystallines from the Atlantic coast to the crest of the Rocky Mountain Front Ranges. This map has, moreover, been converted into a rough relief model.



RECONNAISSANCE-MAP SHOWING
OF SURFACE OF BASEMENT CRYS-
STRUCTURE CONTOUR-

SCALE IN MILES
0
200
400
600
800
1000



APPROXIMATE CONFIGURATION
TALLINES FOR UNITED STATES

INTERVAL = 1000 FEET

SCALE IN KILOMETERS

0 400 800 1200 1600

With these structural maps and this model as backgrounds, it is now possible both to obtain a good visual correlation between the available quantitative and qualitative geophysical data, and the geologic structure, and to plan where new geophysical control-nets can be so spread as to serve most effectively in the geophysical-geological study of the make-up of the United States portion of North America.

Seismic study--A comparison of the structural map and model with the map showing epicentral positions for important earthquakes in the United States discloses, as would be expected, a large degree of correlation between zones of seismic activity and both known and concealed structural lines. The briefest consideration of the similarities between these epicentral and structural maps further emphasizes the desirability of increasing largely the number of seismograph-stations in such situations that through them we can determine whether or not minor adjustments are recurring on old basement-faults, or whether these old fractures are now completely healed.

Gravitational study--New isoanomaly contour-maps, showing quantitatively the regional variations of gravity in large parts of the United States and West Indies have also been prepared at the instance of the Committee, during the past year. These maps were drawn up without reference to the structural data being accumulated, in order that the comparison of the completed gravitational and structural maps would yield results of maximum scientific interest. And this comparison, when made, both confirms the conclusion that gravity-anomalies do have great significance in terms of near-surface earth-structure (as well as in terms of deep-seated earth-conditions), and demonstrates that the establishment of gravitational control-nets over certain large areas would contribute immensely to our knowledge of continental structure -- while at the same time providing a useful reference-system for commercial exploration.

Volcanologic-geothermal study--A map-compilation has also been made showing the geothermal data for the United States, as calculated by Spicer (H. C. Spicer, Rock temperatures and depths to normal boiling point of water in the United States, Bull. American Assoc. Petrol. Geol., v. 20, No. 3, pp. 270-279, 1935) to show temperatures at depths of 5,000 and 10,000 feet -- as derived from Van Orstrand's thermal-gradient data (C. E. Van Orstrand, Normal geothermal gradient in United States, Bull. American Assoc. Petrol. Geol., v. 19, No. 1, pp. 78-115, 1935). Obviously if only enough data, like Van Orstrand's, were now available conclusions of the most far-reaching sort as to temperature-conditions deep within the globe could be drawn from information of the sort presented, and could be substituted for much confusing speculation now afloat.

Other studies--Other studies have been begun by the Committee, and others will be taken up as soon as advantageously possible.

Princeton University,
Princeton, New Jersey

REPORT OF SPECIAL COMMITTEE TO CONSIDER ESTABLISHMENT OF AN AMERICAN JOURNAL OF GEOPHYSICS

J. A. Fleming, Chairman H. A. Marmer, Secretary

C. F. Brooks R. E. Horton F. W. Lee W. W. Rubey C. H. Swick

Report of March 26, 1936--Your Committee finds that the dominating factor in the establishment of an American journal of geophysics is that of finance. As to the need of such a journal and the important services it will perform, there is absolutely no question.

Under the circumstances, the Committee endorses the recommendation made last year by the Special Committee on Journal of Geophysics, that the proposed journal be issued by the offset- or planograph-method of reproduction (see Transactions, 1935, pp. 18-19). It recommends further that the journal be issued bimonthly, with each issue totaling about 200 pages.

The Committee finds that with an editor-in-chief, assisted by a Section editor from each of the sections of the Union, all of whom are to receive no compensation for this work, the cost of a bimonthly planographed journal, including distribution, would be approximately $4200 per annum. Adding the expenses involved in connection with the annual meeting at Washington and the maintenance of the office of the Union, the total annual expenses of the Union would be approximately $5000 per annum.

With a present membership of approximately 725, the annual dues received by the Union is $1450. There is further the annual contribution from the National Research Council of $400, although there is no assurance of continuance. Finally, there is a small margin from the sale of reprints which may be estimated at $200 per annum. In all, the annual income of the Union may be estimated as approximately $2000.

To issue the proposed Journal, therefore, it is necessary to increase the annual income of the Union by $3000. The Committee recommends that this matter be brought to the attention of the members of the Union, and that they be asked to vote on the question of increasing the annual dues to $4. This would add about $1400 per annum, leaving an estimated annual deficit of $1600. This deficit, it is believed, can be met, in part, by institutions contributing part of the cost of publication of papers in the Journal by members of their staffs and, in part, by subsidies from organizations interested in geophysics. A subcommittee of the Committee has been appointed to investigate this latter matter.

Consideration was given to the question of meeting part of the cost by publishing paid advertisements in the proposed Journal. The Committee finds that, at the present time, this would be inadvisable, as the receipts from this source would be nominal for some time to come while the inclusion of such matter would very probably alienate support from the National Research Council and possibly also from other organizations.

In its consideration of this whole matter, the Committee has been aided by N. H. Heck and R. M. Field, who gave generously of their time and thought.

Report of May 1, 1936--The Committee's report of March 26, 1936, upon instruction of the Executive Committee of the Union, was sent to all members. The members of the Union were requested to express approval or disapproval of four proposals relating, respectively, to the establishment of an American Journal of geophysics, the use of the offset method of publication, the issue of the Journal as a bimonthly, and the increase of annual dues to $4.00.

As of April 28, 283 replies had been received. The votes on each of the proposals were as follows:

	No. of votes	Approve (per cent)	Disapprove (per cent)
(1) American Journal of geophysics	268	86	14
(2) Offset method of publication	238	88	12
(3) Bimonthly issue (six issues a year)	233	88	12
(4) Increase of annual dues to $4.00	270	83	17

The 283 replies received represent 38 per cent of the membership of the Union as of March 26, 1936. If it be assumed that the views of this fraction of the membership of the Union is fairly representative of the views of the total membership with regard to the four proposals, it follows that about 86 per cent of the members approve them as against 14 per cent disapproving.

Approximately half the replies were accompanied by comments of one sort or another. A number of these relate to the editorial policy to be pursued in the proposed Journal. But in the present connection, the views of those disapproving the publication of a Journal or the increase in annual dues are of special importance. These latter views may be summarized as follows:

(a) Disapproving publication of a Journal

1. There is already a geophysical Journal in this country, namely, Geophysics published by the Society of Petroleum Geophysicists. This already fills the need for such a Journal.
2. There are already too many scientific Journals; increasing the number adds to the financial burden of libraries and individual scientists, and increases the difficulty of keeping up with current literature in a particular field.
3. The main interest of many of the members of the Union is in but one or two of the Sections, and present Journals in connection with the Transactions are sufficient.
4. A number of Journals issued by various scientific societies are facing serious financial difficulties. The proposed Journal, therefore, should not be undertaken until the financial resources of the Union are adequate for the purpose.

(b) Disapproving increase in annual dues

1. Dues in scientific societies are already a serious burden to the scientist, and an increase of dues in the Union will necessitate the resignation of a number of members.
2. Present nominal dues of the Union encourage membership on the part of those whose interest in the Union is of a marginal nature. Increasing the dues will result in resignation of such members.

The Committee has given careful consideration to the views of those disapproving the proposals, but finds itself in complete agreement with the views of the majority of those replying. Not only will the proposed journal serve the purpose of the Union better than the present Transactions, but it will also bring to the specialist in one field of geophysics a record at frequent intervals of the progress in related fields, which at the present time must be searched for in a variety of specialized journals. Moreover, the proposed journal will serve as a further integrating influence in geophysics by furnishing a medium in which struggling journals in various branches of geophysics may merge without loss to their respective sciences. Geophysics, the journal published by the Society of Petroleum Geophysicists, does not and cannot hope to cover the field of the proposed journal.

The principal difficulty in establishing an American journal of geophysics is that of finances. Even with annual dues increased to $4.00, the present income of the Union falls about $1500 a year short of the amount necessary to publish the journal. It is reasonable to assume, however, that within two or three years the increase in membership of the Union and subscriptions to the journal by non-members will be sufficient to finance the journal. For the first two or three years, however, grants or subsidies to the amount of $1500 per annum will be necessary.

The Committee, therefore, makes the following recommendations:

1. That the Executive Committee of the Union make formal application to organizations interested in geophysics for grants for a period of two or three years totaling $1500 per annum to aid in the establishment of an American journal of geophysics, and that provision be made for merging with this proposed journal of other journals devoted to any one of the geophysical sciences.

2. That, as soon as sufficient grants for two or three years become available, an American journal of geophysics be issued by the offset method as a bimonthly, that is, every other month, and that annual dues in the Union at that time be increased to $4.00.

3. That the editorship of the journal be vested in a board of editors to consist of an editor-in-chief to be named by the Executive Committee of the Union, and an editor from each of the Sections of the Union to be named by the Executive Committees of the respective Sections; the editors to hold office for three years, provided, however, that they be eligible for reappointment at the expiration of any three-year period.

[Note: At the General Assembly of the Union, May 1, 1936, the Executive Committee was instructed to proceed in accordance with the three recommendations made.]

Washington, D. C.

SYMPOSIUM ON RECENT TRENDS IN GEOPHYSICAL RESEARCH

THE PLACE OF GEODESY IN GEOPHYSICAL RESEARCH

William Bowie

The practical and scientific phases of geodesy are so intimately entwined that I shall not in this short paper try to treat them separately. What is of scientific value today may be of immense practical value tomorrow and, conversely, work done in the field of geodesy as an engineering operation may later have great scientific value.

Until recently, geodesy was looked upon merely as a scientific subject involving the determination of the shape and size of the Earth, but it has expanded greatly from this early objective. We now not only use geodetic observations to obtain the dimensions of the Earth, but we are trying to determine the undulations of the surface of the geoid. We have learned that mean sea-level is not an equipotential surface.

Geodetic activities have led to the discovery that the Earth has an outer shell called the crust that must differ in its physical properties from the material that lies below the crust. By means of geodetic data the approximate thickness of the crust has been determined. It is of the order of 60 miles. The actual limit of crustal material should be somewhere between 40 and 80 miles below the surface.

We have not yet been able to determine whether the crustal material is limited by a level surface at some unknown depth below sea-level or whether the lower limit of the crust is an undulating surface. But in any event, it is quite definitely established that for at least the major features of the Earth's surface, such as the oceans and continents, there is a compensating excess or deficiency of matter extending to a limiting depth below sea-level. The ocean-beds are depressed because of material denser than normal lying beneath them. The continents are above the general average elevation of the Earth's surface as a result of the presence of material lighter than normal beneath the continental areas. This condition of approximate equilibrium of crustal material resting upon presumably plastic subcrustal material was given the designation "isostasy" by E. P. Dutton, a famous geologist of the United States. While Dutton outlined the general principles of isostasy in a paper delivered at a meeting of the Philosophical Society of Washingtin in 1889, it was only after a decade or more that the idea of isostasy received much attention.

The geodesists are confronted with a very serious problem in the use of geodetic data in determining the shape and size of the Earth. This difficulty was first encountered in the middle of the last century when attempts were made to compute the shape and size of the Earth from triangulation and astronomical data in India. There were many large station-errors or deflections of the vertical which were recognized as being due to the irregular surface of the Earth. It was quite evident that mountain-masses should deflect the plumb-line to which astronomical observations are referred. Computations were made of the effect of the mountain-masses of India on the astronomical observations but it was found that when corrections to the astronomical data were applied to account for the effect of the attraction of the mountains, the geodetic and astronomical positions of points on the Earth's surface were not brought into as close accord as theoretically should be possible.

Pratt and Airy, two British scientists, suggested that the reason why the application of corrections for the effect of the accumulation of mountain-masses on the plumb-line did not bring the astronomical and geodetic data into accord was that there must be a deficiency of density under land-masses and an excess of density under water-areas that would tend to balance the so-called topography.

The next step in this reasoning was that corrections should be applied to the astronomical data in order to take into account the positive or negative effect of the compensating masses beneath topographic features.

No comprehensive test of this idea of the hydrostatic equilibrium of the Earth's crust was made prior to the beginning of this century. The late John F. Hayford undertook such tests. He used the triangulation and astronomical data of the United States in his first test and found that by the application of the equilibrium-theory, the astronomical and geodetic positions of triangulation-stations were brought into close accord. Later he made similar investigations of the equilibrium or isostatic theory by means of gravity-data. The results of these investigagations substantiated what he had found to be the case when the triangulation and astronomic data were used. Hayford published the results of his first isostatic studies in 1909. Since then much work has been done in the field of isostasy by members of the United States Coast and Geodetic Survey and by geodesists in other countries. We can now quite safely say that isostasy, in its general aspects at least, can be accepted as a scientific principle.

The seismologists have found that there are certain layers of material near the surface that reflect or refract the seismic waves. These materials, having what may be called abnormal physical properties, extend to a depth of not more than 40 km below sea-level.

Some have claimed that the thickness of the Earth's crust of approximately 40 km determined from the seismological data is the limit of material within which the isostatic compensation lies. This, it seems to me, is probably not the case. The geodetic data, theoretical and observed, require a depth of approximately 100 km to bring them into agreement. A depth of only 40 km would still leave large outstanding differences between the theoretical and observed values of gravity and the astronomical and geodetic latitudes and longitudes. There would be a very definite relation between the height of the topography and the so-called anomalies for a depth of only 40 km.

No doubt this outer material, composing the layers found by the seismologists has residual rigidity but is it not possible that the outer portion of the material lying below the 40-km depth could also have residual rigidity? In order to have isostatic adjustment of topographic features, we must have material of residual rigidity, otherwise columns of the Earth having different surface-heights could not remain close together without a transference of material from one to the other, tending to make the material form in layers, each having a uniform density.

In my judgment, this question of the depth of the Earth's crust or the so-called depth of compensation is important. There have been great changes in the elevations of certain portions of the Earth's surface. It may be that all parts of the Earth's surface have changed materially in elevation during the sedimentary age, approximately one and a half billion years. It is most probable that there is no such thing as any part of the land-surface of the Earth being stable. This is indicated by the thousands of earthquakes occurring yearly and by the evidence of faulting and folding, and of marine sediments now well above sea-level. We do not know much about ocean-areas as far as their stability is concerned, but we are aware of the fact that there are many earthquakes occurring under oceans and the epicenters of most of those are near the continental margins, ocean-troughs, and other broken ground. The troughs of the ocean are apparently not permanent features. How long they have existed and what will be their future, no one, of course, can tell.

Since there have been great changes in the elevation of portions of the Earth's surface, and perhaps all of it, we must conclude that those changes are due to a change in density of crustal material or to a regional horizontal compressive force or to a combination of the two. There is considerable evidence, I believe, in favor of the idea that earthquakes are due to local causes and not to world-wide ones. Is not this an indication that the cause of the change of elevation is due to expansion or contraction of crustal material?

In any event, it makes no difference what is the cause of the changes in elevation. We must have some material within which forces can act to cause the change. If we have horizontal compressive forces to cause uplifting of mountains and plateaus, we could not do that with a crust approximately 40 km in thickness. Then again, suppose the changes in elevation are due to changes in density of crustal material. We must have enough material within which the changes can take place for otherwise the changes would be enormous.

I am rather inclined to favor a thickness of the crust of approximately 100 km. This does not necessarily mean that there is a difference in the chemical composition of the material above and below the depth of compensation. It does mean, however, that the physical properties of the material above that depth are such that the material has residual rigidity while presumably below the depth of compensation residual rigidity is lacking.

I think we can ignore the question for the present of whether we have the Pratt or the Airy hypothesis of isostasy. If the Airy, then the continents are underlaid by so-called roots that extend down into what would normally be subcrustal space. For the Pratt idea, we should have more or less uniform depth of crustal material; but of course the lower surface of the crust cannot be a level one. There are changes now going on which depress crustal material under areas of sedimentation and elevate crustal matter that lies under areas of erosion. This would mean that for certain areas some crustal material is depressed into subcrustal space and for other areas the subcrustal material enters crustal space.

It has been claimed that the international spheroid or ellipsoid derived from triangulation and astronomical data in the United States by the late John F. Hayford, when with the United States Coast and Geodetic Survey, does not truly represent the geoid surface of this, that, or the other country. This is true because this international ellipsoid is based upon the principle of isostasy. All astronomical observations which are referred to the direction of gravity are affected by the so-called deflections of the vertical by the irregular terrain. The plumb-bob will be deflected towards mountains and plateaus and away from valleys and bodies of water. But it is believed that when the isostatic principle is used, which involves the application of the effect of the topographic masses and their isostatic compensation to the astronomical data, the spheroidal or ellipsoidal surface derived for any large continental area will be very close to the true spheroidal surface for the whole Earth.

The geoid surface for a continent that is high in its center and low at its margins will have a radius of curvature that is shorter than the radius of curvature of the spheroid for the same area. On the other hand, if the continent is low in the center and fringed by high mountain-masses, the geoid surface will have a radius of curvature that will be longer than that of the spheroid for that area.

If isostasy were not true, the variation of a geoid surface from the spheroid would be rather large. It has been estimated that such deviations might be 1000 feet or more. The large elevations of the geoid with respect to the spheroid would be in continental areas while the greatest depressions of the geoid below the spheroid would be over the deepest parts of the oceans. It is reasonably certain that the geoid does not deviate from the spheroid more than 100 or 200 feet at any place. This is indicated very clearly by the deflection of the vertical and gravity-data.

A knowledge of the shape and size of the Earth and of its curvature for different latitudes is essential to the making of charts of the water-areas and maps of continents and islands. Without these data supplied by the geodesists, it would be practically impossible to carry on accurate mapping and charting operations over large areas of the Earth's surface.

Since isostasy has been substantiated we can apply this principle in economic geology. Gravity-observations can be made over an area to be investigated and, after the corrections have been applied to the observed values of gravity to account for the elevation of the point of observation above sea-level, the attraction of the topographic masses, and the effect on the gravity-observations of the compensation of topography, we have left a so-called anomaly at each of the gravity-stations. These anomalies are due to the unavoidable errors of observations which in most cases are small, to the uncertainty in the topographic masses due to errors in the maps, to the deviation of the crustal block below the station from the isostatic conditions assumed, and to deviations from normal of the densities of material that lie close to the point of observation. It is this last effect that is undoubtedly the largest. It has been found by geophysicists working in the petroleum industry that gravity-data can be used in their work. They are able to detect regions of abnormal densities of material that may lead to the discovery of geological conditions that have economic importance in the oil and salt industries.

If the area investigated by the geophysicists is comparatively small and practically level, the principal of isostasy need not be considered in the investigations designed to discover minerals including oil, gas, and salt; but if one wishes to compare the results obtained at gravity-stations in a large area, then surely the isostatic reductions of the stations must be made in order that the data for widely separated parts of the region may be correlated.

Arcs of triangulation, at first extended over a continent for the purpose of determining the shape and size of the Earth, were found to be of such great economic importance in the location of boundaries of nations and subdivisions thereof, and as the framework for accurate maps, that now triangulation is extended over the area of a country for the boundary- and map-purposes alone. In practically all cases the results are of such high accuracy that they can be used in any new determination of the shape and size of the Earth and in the studies involving the determination of the shape of the geoid surface under the area covered by the triangulation.

In the United States there are now 67,000 miles of arcs of first- and second-order triangulation. This is more than two and a half times the circumference of the Earth. It is hoped that about 50,000 miles more of arcs of triangulation can be added to the national net of the United States in order that a framework may be furnished for accurate maps and boundary-surveys for all parts of our area. With such a large amount of triangulation and the thousands of astronomical stations that are or will be coincident with triangulation-stations, we should be able to make a study of the shape of the surface of the geoid of this country that should give results of great scientific interest and importance.

I think the most important contribution of geodesy to geophysics is in the furnishing of a base for topographic maps. A map is a representation of a portion of the Earth's surface. If accurately made and based on geodetic surveys, it will show the position and elevation of each topographic feature, natural or artificial, and the distances and directions between any two points shown on the map. By contours the maps show the slope of the ground. They may therefore be considered as accurate in position, distance, direction, elevation, slope, and area. It seems to me each piece of geophysical work needs for its proper execution just such information as the map may show.

We in this country are very poorly mapped. While 47 per cent of our area is covered by topographic map-sheets, yet more than half of those map-sheets are so old and so out-of-date that they are of practically no value for modern-day uses. It would appear, then, that only about 25 per cent or less of our three million square miles is covered by maps that are considered to be satisfactory. Even some of these good maps should be revised in order to show new features that have appeared since the maps were made.

We have now a very easy method of revising a map. It consists of flying over the area in an airplane and taking pictures of the ground. The pictures can be compared with the map and the draftsman or cartographer can readily see what changes have occurred since the map was made.

There is no question but that a knowledge of the terrain is of value to the scientists, engineers, economists, and many others. A good map must be accurate in position, distance, direction, elevation, and slope. Such a map can only be made when there is a framework of geodetic surveys on which the topographic mapping is based. If there were no scientific phases to geodesy whatsoever, yet the work would have to be done to meet the practical needs of the map-maker.

One of the branches of geophysics that has come to the fore in recent years is seismology. There is nothing of greater importance in the field of science than to safeguard life and property. While in this country we have been rather fortunate in not having many major catastrophes resulting from earthquakes, yet it has been estimated by Mallet that throughout the world during the past 4000 years some 13,000,000 people have been killed by earthquakes. One can readily understand the importance of learning all that is possible as to the causes of earthquakes and the locations of areas in which they occur in order to safeguard so far as is practicable life and property.

The geodetic surveys in the form of triangulation and leveling are of importance in seismic investigations. Earthquakes are caused by the rupturing of material and the ruptures frequently cause movements of the surface of the Earth. By repeating observations along lines of levels and at the triangulation-stations, it is possible to detect distortion of the Earth's surface that might later result in earthquakes. After an earthquake has occurred, the geodetic observations for the stations in the vicinity of the epicenter can be repeated with a view to learning whether the cause of the earthquake is local or regional. If the former, only a small area would be affected, that is, only the stations near the epicenter would have changed their geographic positions or elevations. If the cause of the earthquake is regional, then one would expect stations for great distances from the epicenter to have been changed in position or elevation or both.

Some work has already been done in the United States with a view to determining what movements occurred at the time of earthquakes, but a very much larger amount of such work has been done in Japan. No doubt, geodesists will be called upon frequently by seismologists to repeat geodetic observations in order to furnish data that will be of value in research in the field of seismology.

Geodesy has been extended in recent years to the sea. Observations now can be made on a submarine for the determination of the values of gravity. The results of the gravity-observations already made at sea have given us information regarding the densities of crustal material below ocean-areas. These observations made on the submarine should be supplemented by gravity-stations along all of the coasts of the continents and on oceanic islands. A comprehensive gravity-survey of the world would furnish data invaluable to geophysicists and geologists who are trying to interpret the processes that have been at work during geological time to change the configuration of the Earth's surface.

The adjustment of the combined leveling nets of the United States and of Canada show clearly that mean sea-level at tidal stations along a continental coast does not define a level or equipotential surface. An adjustment of the combined nets was made with only one tidal mean sea-level plane held as having zero-elevation. That plane was at Galveston, Texas. Of course, there are some errors in the leveling due to unavoidable accidental errors and to certain systematic and constant ones, but the net is so strong that the differences in the elevation of mean sea-level for different tidal stations are of the right order of magnitude. Table 1 shows the elevation of mean sea-level at tidal stations along the Atlantic, Gulf, and Pacific coasts referred to Galveston as zero.

Table 1--Relative elevations of mean sea-level determined by the 1929 special adjustment, based on Galveston, Texas

Station	Relative elevation of mean sea-level
	meter
Gulf Coast	
Galveston, Texas	0.00
Biloxi, Mississippi	-0.09
Pensacola, Florida	-0.05
Cedar Keys, Florida	-0.08
Atlantic Coast	
St. Augustine, Florida	-0.27
Fernandina, Florida	-0.20
Brunswick, Georgia	-0.16
Norfolk, Virginia	-0.14
Old Point Comfort, Virginia	-0.28
Cape May, New Jersey	+0.02
Atlantic City, New Jersey	+0.03
Annapolis, Maryland	-0.17
Baltimore, Maryland	-0.18
Perth Amboy, New Jersey	+0.01
Fort Hamilton, New York	+0.03
Boston, Massachusetts	+0.07
Portland, Maine	+0.12
Yarmouth, Nova Scotia	+0.05
Halifax, Nova Scotia	+0.08
Father Point, Province of Quebec	+0.20
Pacific Coast	
San Diego, California	+0.33
San Pedro, California	+0.31
San Francisco, California	+0.34
Fort Stevens, Oregon	+0.59
Anacortes, Washington	+0.45
Seattle, Washington	+0.48
Vancouver, British Columbia	+0.50
Prince Rupert, British Columbia	+0.58

It will be seen that there is a downward tilt of the Gulf waters to the eastward of Galveston. Then, there is an upward tilt of waters from tidal stations in Florida northward along the Atlantic Coast. There is a tilt upward of mean sea-level along the Pacific Coast northward from San Diego. The average mean sea-level determination by tidal observations at Pacific Coast stations is about 0.5 meter higher than the average for the mean sea-levels at tidal stations of the Atlantic and Gulf coasts.

This tilting of mean sea-level is a very interesting geophysical problem and challenges one to find the cause of the deviation of the sea-level surface from an equipotential one. It is probable that the deviations found are caused by variations in the densities of oceanic waters, prevailing directions of wind, and differences in barometric pressures for different latitudes. I have understood that the density-determinations of waters of the Pacific indicate that they are less than those for the Gulf of Mexico and the Caribbean Sea. It would be of interest if we could have the leveling nets of other continents adjusted in a manner similar to that for the United States and Canada to see whether there are deviations of mean sea-level from an equipotential surface for the surrounding waters of all of the large land-areas of the Earth.

To the astronomer an accurate knowledge of the velocity of light is very important in his investigations. In certain phases of geophysics the velocity of light is also of importance. It is only by means of geodetic surveying that very accurate lengths of base-lines used in the velocities of light can be determined. The United States Coast and Geodetic Survey measured a base-line between San Antonio Peak and Mt. Wilson, California, some 22 miles in length, over which Professor Michelson made his determination of the velocity of light. Then again, the mile tube, used first by Professor Michelson and then by Dr. Pease, was measured three times by the Coast and Geodetic Survey.

The Wegener Hypothesis has received a great deal of attention in recent years and deservedly so. It is based upon the idea that we have perfect isostasy. This implies that the sial which lies under the continents and islands has residual rigidity while the sima is plastic and offers no resistance to the movement of the blocks of sial.

Many students of the Earth's crust feel that the Wegener Hypothesis does violence to certain mechanical principles, but, in any event, it is something that should be looked into. The geodesists have cooperated with the astronomers in two great world-wide longitude-campaigns which were designed to furnish the basis for determining whether continents and islands are wandering over the face of the Earth. Nothing has been found up to this time that would substantiate the Wegener Hypothesis, but we cannot tell what the future may disclose.

Of great importance in carrying on geodetic and geophysical investigations of all kinds is the splendid time-service of the United States Naval Observatory. The officials of the Navy Department are to be commended for the help they have given to science by having such time-service furnished. The hourly signals that are now sent by radio from the Naval Observatory are extensively used by geodesists and geophysicists. It is hoped that this service may be extended to cover those hours for which time-signals are not now given.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RECENT DEVELOPMENTS IN THE GEOPHYSICAL STUDY OF OCEANIC BASINS

Richard M. Field

The history of the application of geophysical methods to the study of oceanic basins and their margins shows an encouraging acceleration of activity since the last meeting of the American Geophysical Union. The determination of gravity at sea has been continued by Holland, Italy, France, and Japan, with the help of their respective navies. Outstanding in marine gravimetric surveys has been the recent comprehensive and arduous expedition of Dr. F. Vening Meinesz, not only the pioneer but still the most active exponent of this type of research.

During the past year, plans have been completed for a gravity-expedition to such significant areas as the southeasterly extension of the West Indian Island Arc and the submerged margin of eastern North America. This will be the third marine gravity-survey which has been expedited by American agencies since 1929, and illustrates the splendid cooperation which geophysicists and geologists have received and are continuing to receive from the United States Navy.

Of equal importance has been the continued topographic mapping of the submerged continental shelf by the United States Coast and Geodetic Survey. Geodesists and geologists are particularly indebted to this agency for the accurate delineation of a number of amazing submarine canyons off both the Atlantic and Pacific coasts. Thus, as further marine topographic and gravity-surveys have been planned and executed, geologists have turned their attention increasingly to the possible relation of the accumulated data to the topography, stratigraphy, and structure of oceanic basins and their margins. While the geophysical study of submarine geology is still in its elementary stage, the past year has also seen the invention and successful application of new and extremely useful techniques. H. C. Stetson, of Harvard University, with the important cooperation of the Woods Hole Oceanographic Institution and the Geological Society of America, has supplied us with samples of the lithology and paleontology of the side walls of the submarine canyons; C. S. Piggot, of the Geophysical Laboratory, with the cooperation of the same institutions, as well as that of the duPont Company, has procured eight- to ten-foot cores of deep-sea sediments; and Maurice Ewing and N. H. Heck have adapted the seismic method of the oil geologist to submarine geology, giving us our first definite information as to the thickness of the sedimentary rocks at the edge of the continental shelf. The last-mentioned accomplishment is particularly illustrative of the cooperative method in research. Conceived and planned by our Committee two years ago, its successful operation is due not only to Ewing and Heck, but also to the splendid support of numerous other individuals and institutions. Among the latter, special mention should be made of the Lehigh University, the Geological Society of America, the Woods Hole Oceanographic Institution, the United States Bureau of Mines, and the United States Coast and Geodetic Survey.

The accomplishments of Stetson, Piggot, and Ewing are so recent that there has not been sufficient time for geodesists and geologists to fully appreciate the many problems associated with the new data. As an illustration, however, of the stimulus which the geologist--if not geology--has recently received from the geophysical exploration of oceanic basins and their margins, let us take as a single example, submarine canyons. First, let it be clear that the original discovery and subsequent discussion of this remarkable type of submarine topography was largely accidental and in no way the result of a search for further geological data, in support of other geological data, or in the support of preexisting hypotheses. Indeed, at present, the discovery of these canyons is as generally helpful to existing geological theories and hypotheses as would be the sudden discovery of new biological data which appeared to refute the theory of evolution.

What to do with submarine canyons has been an embarrassing question ever since they were first called to the attention of geologists by J. W. Spencer in 1903. The recent revival of interest in the problem is chiefly due to new data obtained by the use of modern geophysical methods of sounding and positioning at sea and the skilful mapping of these data by F. P. Shepard. At the present time there are three major theories as to the origin of the canyons, and a fourth is impending. It should also be noted that each theory involves important geophysical, as well as geological, postulates. Shepard suggests that the canyons are entirely of subaerial origin, cut during the Pleistocene, when the ocean-level was reduced approximately 3000 to 6000 feet by the temporary accumulation of ice on the continents. Daly, the exponent of a similar hypothesis in relation to the origin of coral reefs, will agree to the reduction of ocean-level some 250 feet, but cites what he considers insupportable geophysical difficulties in such a reduction of ocean-level as demanded by Shepard. Daly, therefore minimizes the evidence as to the subaerial origin of the (now) submarine valleys, and suggests that they have been eroded by the submarine scour of exceedingly muddy and super-saline waters, which he postulates occurred at the margins of the Pleistocene ocean.

H. H. Hess and Paul MacClintock agree with Shepard that the submarine canyons must be of subaerial origin, the result of the requisite reduction of sea-level. They, however, in order to overcome what they consider to be the difficulties of a 20,000- to 50,000-foot ice-sheet on the continents, suggest what may be another still more comprehensive astronomical, geodetic, and geophysical difficulty, namely, a relatively rapid and recent change in the ellipticity of the surface of the oceans, due to a sudden decrease in the rate of the rotation of the Earth, and the consequent drawing of the oceanic waters into the polar latitudes. A careful analysis of the above-mentioned theories leads to the conclusion that all of these theories, with the possible exception of Daly's, may be tested by available geophysical techniques. The principal difficulty with Daly's thesis is that it attempts to refute the distinctive physical features of the canyons themselves; and, in order to avoid too great a reduction in sea-level, postulates a set of conditions not only peculiar to the time at which the canyons were formed, but which probably left no recognizable trace of their specific activity. This brief summary of this year's theories concerning the origin of submarine canyons is not intended as a criticism of any or all of them, but rather as an illustration of the amount of geological speculation which has been so suddenly aroused by the recent addition of more accurate data on submarine topography, provided by geophysical techniques.

Though a relatively large number of marine gravimetric determinations have been made during the past twelve months--Vening Meinesz alone having completed 239, not including 26 land-stations--it will be several months before even a preliminary estimate can be made of their geological significance. Dr. Vening Meinesz is expected to make his first report in September at the Edinburgh meeting of the International Union of Geodesy and Geophysics. It is particularly significant that this report should add considerably to our knowledge of the character of the lithosphere under the Atlantic Ocean.

The outstanding original adaptations of geophysical techniques to the study of submarine structural geology, during the past year, have been in the field of seismology. It is interesting to note that these new seismic data apply particularly to the sub-Atlantic lithosphere. In order to appreciate the full geological significance of these data, however, it is necessary to review the history of the geological dictum of the relative permanency of continents and ocean-basins, which has depended for a number of years on two rather meager types of evidence: (1) A few samples of deep-sea sediments, unlike those composing the sedimentary rocks of the continents, and (2) the submerged and cliff-like margins of the continents. The addition of gravity-data, for both the subaerial and suboceanic areas of the lithosphere, combined with the principle of isostasy which is postulated not only upon geophysical but also upon geological evidence, have also tended to confirm the geologist's belief in the permanently depressed and submerged condition of a large portion of the lithosphere throughout most of geologic time. This belief in the ancient origin of the Atlantic Basin has had a profound effect on geological thought because the development of the principles of historical geology has been chiefly due to the stratigraphic and tectonic studies of the more or less disconnected but correlated margins of the North Atlantic. In order to explain the origin of the observable distribution of formations and fossil organisms, stratigraphers have attempted to solve this difficulty by imaginary land-bridges; not daring, apparently, to question the major structural hypothesis which had been largely postulated on a few samples of deep-sea sediments. Some 20 years ago, Alfred Wegener suggested that the Pacific was the only original ocean-basin and that the pattern of the continents was like a picture-puzzle, North and South America having broken away from Europe and Africa at the close of the Paleozoic. According to this theory, the Atlantic is supposed to have been growing bigger and bigger (at the expense of the Pacific) through the Mesozoic and Tertiary eras. The Wegener theory has been championed by Daly, and also a number of structural geologists; but, in spite of the fact that it was put forward largely to account for the Paleozoic paleogeography of the Eastern Hemisphere, most Paleozoic stratigraphers, such as Charles Schuchert, have disapproved of it, preferring, as the choice of lesser evils, to stick to their "land-bridges."

In summation, all of the theories so far advanced to account for the present pattern of the face of the Earth suggest that the Atlantic is underlain chiefly by sima, not by sial, except possibly for some hypothetical sunken and relatively narrow land-bridges of pre-Mesozoic rocks. It is, therefore, particularly interesting to note that, during the past year, Gutenberg and Richter, after making a careful study of the Atlantic seismic reflections, provided us, according to Heck, with the following statement: "Seismograms were selected to give reflections in all parts of the Atlantic Area, and at such distances as to give a clear discrimination between continental and Pacific types of reflection. All cases agree much better with the mean data for continental reflection than with those for Pacific reflection. This confirms the result already found from the velocities of surface-waves, that the floor of the Atlantic Ocean is a region in which the surface-layer has physical properties similar to those of the continental surface-layer. The thickness of this layer cannot be determined from these data on reflections alone, but it must be at least a large fraction of the wave-length, which in most cases is between 20 and 30 km." It is important to note that the latter figure is approximately one-half of the 60 km which is given as the wave-length of the continental lithosphere. Further, upon comparing the Atlantic with the Pacific seismograms, it is seen that, while there is a distinct boundary between the sub-Pacific and continental lithosphere, no such boundary delimits the Atlantic Basin. The analysis of "earthquake-waves," therefore, not only suggests the Atlantic to be everywhere underlain by a considerable thickness of continental rocks, but also intimates that the Pacific continental margins are of much greater structural significance than those of the Atlantic. This suggestion is still further strengthened by the recent "artificial seismic" profile from the edge of the Atlantic Cretaceous overlap to the continental margin, where the sedimentary rocks composing the bathyal slope have been proved to be only one-half the thickness of the stratigraphic column overlying the greatly downwarped pre-Cretaceous contact.

Combining all of the seismic evidence produced during the last few months, it would appear as if the present topographic limit of the Atlantic continental margin had no particular structural significance; that is, so far as an ancient structural delimitation of continental block and ocean-basin is concerned. It is possible, therefore, that the sub-Atlantic lithosphere constitutes a vast area of downwarped pre-Cambrian and Paleozoic geology, fully comparable in the complexity of its subsidiary stratigraphic, structural, and paleogeographic features to the upwarped pre-Cambrian and Paleozoic geology of the surrounding continental areas. If this be true, Schuchert's necessary but modest postulate of a limited Appalachia is but a structural element of the whole of the sub-Atlantic lithosphere, and stratigraphers are finally relieved of the insupportable structural difficulties which they now encounter in their Paleozoic paleogeographic problems. It is not implied that the downwarp of this great pre-Mesozoic continent of Atlantica was relatively rapid, or that it took place all at once. In the late Tertiary there may still have been some subaerial remnants whose land-areas were temporarily enlarged by the particular climatic events of the Pleistocene. What is implied, however, is that, through the pre-Cambrian and Paleozoic history of the Earth, the Atlantic Region was characterized by seas, lakes, rivers, mountains, sediments, marine and terrestrial organisms respectively similar to, and coexistent with, those of the continents.

The particular value of any theory or hypothesis as to the origin of the Atlantic Basin must be judged, for the present, according to the emphasis which each places on: (a) The exact details of the further physical evidence to be sought; (b) the particular area, or areas, to be surveyed; and (c) the geophysical methods to be employed.

In review, the recent progress in the geophysical and geological study of oceanic basins and their margins has been chiefly characterized by:

(1) The continued international activity in the determination of gravity at sea.
(2) The continued international activity in submarine topographic surveys. Special mention should be made of the perfection of sounding and positioning methods, and their application to the surveying of the continental shelves, by the United States Coast and Geodetic Survey.
(3) The development and successful application of a bottom-sampler for procuring sedimentary cores of from eight to ten feet in depth.
(4) The successful application of the seismic method to the study of submarine stratigraphy and structure.
(5) The increasing interest which is being shown by both geologists and geophysicists in the physical study of ocean-basins.
(6) The assurance that a comprehensive and cooperative plan for the physical exploration of ocean-basins will be discussed at the Edinburgh meeting of the International Union of Geodesy and Geophysics this fall.
(7) Most impressive of all has been the splendid cooperation of individuals and institutions (both private and governmental) in the promotion of this new field of research under the leadership of the American Geophysical Union.

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MODERN TRENDS IN SEISMOLOGICAL RESEARCH

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A survey of the field of modern research in seismology will reveal a surprising activity in three distinct fields: The field of pure seismology; the field of engineering seismology or of seismological engineering; and the field of applied seismology or of seismic prospecting. We may consider these briefly in succession.

In pure seismology emphasis is shifting from average results and statistical studies to the intensive investigation of individual regions and of individual earthquakes. Even in those cases in which genuine contributions have been made along statistical lines, as, for example, in the exhaustive paper by Jeffreys and Bullen "On the times of transmission of earthquake-waves" (Bur. Central Séis. Pub., A, Travaux Scientifiques, No. 11, 1935), the material has been sifted in such a manner as to bring out the distinguishing characteristics of earthquakes by means of particular constants. Also, in the three papers "On seismic waves" by Gutenberg and Richter (Beitr. Geophysik, v. 43, pp. 56-133, 1934; v. 45, pp. 280-360, 1935; v. 47, pp. 73-131, 1936) individual earthquakes are discussed. At the Fourth General Assembly of the International Union of Geodesy and Geophysics at Stockholm and again in the Fifth Assembly at Lisbon, the pressing need for the intensive study of individual earthquakes was urged. To be sufficiently profitable to justify the labor, the earthquake chosen for study should be so placed with reference to observing stations as to permit extensive cross-checking between data of different types; and to be entirely satisfactory the earthquake should have originated in a region where there is a fair distribution of good stations, equipped with modern seismographs recording on an adequately open time-scale and with automatically registered radio time-signals. In the past the number of earthquakes which satisfied these conditions were few, but the rapid development of seismographic stations and apparatus in recent years has greatly broadened the possibilities. In the second place, the earthquakes so chosen should have begun with a clear impulse which can be followed from station to station so that ambiguities in regard to arrival-times may be excluded. The number of investigations of this comprehensive character has been steadily increasing. Examples in the case of normal earthquakes are: The studies of the Montana and Texas earthquakes and of many smaller shocks in northern and central California by Byerly and his associates; the studies of the Long Beach and other earthquakes in southern California by Wood, Gutenberg, and their associates; of the Tango earthquake, the Saint Lawrence earthquake, and others by Hodgson; of the Hawke Bay and Long Beach earthquakes by Dahm; of the Kansu earthquake by Mme. Labrouste; of individual series of observations in several particular earthquakes by Miss Lehman; and of the northern California and South Pacific earthquakes by the writer.

Plutonic or deep-focus earthquakes are occupying the attention of a large number of seismologists both because of their unique character and of the physical and geological implications involved in their occurrence at depths of hundreds of kilometers. Once more, in this case, the greatest progress has been made through the investigation of individual plutonic earthquakes by Wadati, Scrase, Stechschulte, Brunner, and others.

Since the rise of instrumental seismology, the investigation of the structure of the Earth's interior has occupied a prominent place in the minds of seismologists, but the great improvement that has taken place in the available data and in the distribution and character of seismographic equipment now makes it possible to attack problems of detailed structure not only in the Earth's crust but at greater depths which were quite beyond the hopes of earlier investigators like Knott and Wiechert. Seismological methods have been applied with success to the scientific study of crustal structure in the United States, Germany, Poland, Russia, and elsewhere; and their use may be expected to increase in this country under the stimulation of the two committees of the American Geophysical Union--the one "On the Geological and Geophysical Study of Ocean Basins" under Field's chairmanship, and the other "On the Geological and Geophysical Study of Continents" headed by Thom. Doubtless, also, this type of research will profit greatly by the phenomenal growth of commercial seismic prospecting. However, it is in the study of the Earth's deeper structure that seismology has no rival. Splendid work of a more or less statistical character has been done by Gutenberg, Witte, and others. But investigations based exclusively on the data from one individual tectonic earthquake after the other are opening up a new line of evidence which supplements that from plutonic earthquakes. The studies by Dahm on the variation of velocities with depth underneath Japan and California seem to indicate a difference of structure which penetrates practically to the Repetti discontinuity at a depth of a little less than 1000 km. These seemingly deep-seated inhomogeneities, combined with the extreme violence of some plutonic earthquakes and the apparent predominance of shear-energy in some of these earthquakes have stimulated interest anew in the mechanisms as well as in the causes of earthquakes in general. However, it must be admitted that much that has been written on the subject is in the nature of speculation, and it is necessary to keep in mind the fact that a large majority of strong earthquakes appear to originate at depths of 10 to 15 km and have no demonstrable connection with volcanic or magmatic activities; that, in the second place, the very numerous earthquakes which seem to depend on the eruptive processes of volcanoes are very shallow indeed in origin and weak in total energy; and that, thirdly, there is a large and very important minority of plutonic earthquakes that have their focus in the subcrustal material far beneath the level of the Mohorovičić discontinuity though there is no evidence that they ever occur at depths greater than the Repetti discontinuity. While it is interesting to speculate on the geological theories of Daly, Chamberlin, De Lury, Branca, and others, and while these theories afford certain checks on any mechanism postulated to explain plutonic earthquakes and, for that matter also, normal earthquakes, nevertheless, the real test must come from the observed characteristics of the earthquake-motion as manifested in the seismographic records themselves. Hence, a number of attempts have been made particularly by Japanese seismologists to set up geometrical models in order to determine from mathematical theory the direction of faulting needed to explain the observed distribution-patterns of the first recorded movements.

In fact, there has been in recent years a growing tendency to reexamine all the accepted postulates underlying each of the conclusions derived from the mathematical theory of seismology. This healthy questioning of accepted theory has been directed not only toward a more detailed analysis of the effect of heterogeneity, of imperfect elasticity, and of discontinuities, but also toward a better understanding of the character of seismic motion itself and particularly of nature of actual seismic waves and of the response of seismographic systems to these waves. Thus we have the theoretical investigations of Sezawa, Kawasumi, Jeffreys, Stoneley, Uller, O'Donnell, Maryshkina, Slichter, and many others. The same desire to get behind assumptions and probabilities and to secure a solid foundation of incontestable facts has led to the shaking-table experiments by Dyk, McComb and Wenner, Miss Roess, Lacoste, and others.

The study of the geography of earthquakes has continued to develop through the compilation and publication of lists of earthquakes, through the determination of epicenters in a preliminary way by the cooperation of the United States Coast and Geodetic Survey, Science Service, and the Jesuit Seismological Association in this country, by the International Bureau at Strasbourg and by many individual stations, and in a more comprehensive manner for the International Seismological Summary by Hughes and Miss Bellamy at Oxford, and finally with surprisingly high precision by individual investigators of particular earthquakes.

Passing now to the second field of seismological research, that of engineering seismology, we find that a great impulse was given to this type of investigation by the agitation of such men as the late John Freeman, by the lessons of the Long Beach and other recent earthquakes, and by the active interest of Captain N. H. Heck, and by the wise use of a small portion of the relief funds. Under the general direction of the United States Coast and Geodetic Survey, strong-motion seismographs of the Wenner, Weed, and other types have been developed and installed in considerable numbers, especially in California, and records have been obtained of the actual periods, amplitudes, and accelerations of destructive earthquake-vibrations very near their origin. In order to compare the results obtained from these records with those secured in the case of large numbers of smaller earthquakes recorded near their origins by permanent stations, a count was made by Gutenberg of thousands of periods in order to determine which periods were dominant. Another line of attack was the investigation of the vibration-characteristics of buildings, dams, water-tanks, and other structures. For this purpose portable seismographs were installed and the natural vibrations measured at different points in the structures. Since there has been a great difference of opinion in regard to the factors most responsible for damage, it was necessary to secure measurements of as many factors as possible in order to determine which, if any, are the controlling factors. One condition that is considered by many to be most important is resonance of the earthquake-frequencies with the natural frequencies of the structures and of their parts and also of the ground on which they stand. To secure information in regard to resonance, eccentric vibrators of simple construction were used by Ramspeck and by Köhler in Germany and a much more elaborate vibrator was designed and used by Jacobson and Blume in California. At the same time various theoretical studies were made of the behavior of ideal structures to be used in comparison with the observations. A further attack that promises to be effective is the testing in the laboratory of scaled models. This was done in various ways in the engineering laboratories of Stanford University, the University of California, California Institute of Technology, and in a new form by Ruge at the Massachusetts Institute of Technology.

The third field in which vigorous research is being prosecuted is that of applied seismology. Although it is much more difficult to give a just appraisal of the trends in this field because of the lack of adequate publication, nevertheless, a very encouraging change of attitude on the part of those executives previously responsible for excessive secrecy is manifested in the organization and large membership of the Society of Petroleum Geophysicists and in the presentation of excellent programs of research papers within the past few months at Dallas, Texas, and at Tulsa, Oklahoma, as well as in the publication of these papers in the new Journal, Geophysics. The Russians also have been very active in research and publication in the applied field. While much of the research is directed toward the perfection of a seismographic apparatus, there are outstanding investigations in progress on the behavior of elastic waves in various geologic structures. These investigations are not only of a theoretical character but also experimental. Rieber, as a sequel to his paper on his sound-track apparatus for the analysis of directional effects in a complex geologic structure, presented at Tulsa the results of the application of short-wave sound photography to the laboratory-determination of paths of waves by reflection, refraction, and particularly by diffraction in folded and faulted structures of various degrees of complexity through the use of mechanical models similar to those used in acoustical investigations. Other groups in this country and abroad are investigating the mechanism of transfer of energy from an explosive to an elastic medium.

The most encouraging feature of present-day trends is the increasing realization of the fundamental unity and interdependence of many of the problems that underlie not only all fields of seismological research but also of many seemingly distinct fields such as geology, engineering, architecture, and insurance. It is particularly in the close cooperation of geologists and physicists with the seismologists that the greatest progress is to be hoped for in the solution of the difficult problems of seismology.

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RECENT PROGRESS IN THE PHYSICAL INTERPRETATION OF SYNOPTIC WEATHER-CHARTS

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Meteorological research is not characterized, to as great an extent as are many other fields of science, by prominent trends; that is, current meteorological literature is not in general dominated by discussions of any one particular topic or problem, but rather many widely different problems are constantly being subjected to investigations that are comparable in extent and that result in steady, even if not spectacular, progress throughout the field of meteorology. It occasionally happens, however, that for one reason or another an especially significant development takes place in connection with some particular problem, and for a time commands unusual attention. As past examples, there may be cited the striking development of the theory of turbulent motion in the lower atmosphere and its application to the explanation of a wide range of meteorological phenomena, which began with the work of G. I. Taylor in 1915; and the extensive work on the polar-front theory of atmospheric circulations, initiated by the Norwegian meteorologists about 1918.

Even a very brief examination of the outstanding meteorological research during recent years reveals a continually increasing tendency to emphasize the physical interpretation of atmospheric phenomena, in an effort to base investigations explicitly on the principles of physics rather than to be content with only the descriptive, empirical, and statistical studies that formerly were so predominantly characteristic of meteorology. It is a question of great interest and importance whether these advances in the physical theory of atmospheric phenomena can be utilized in practical applications; and it is one of the most noteworthy of recent tendencies in meteorological work that active efforts have for some time been in progress to extend the direct application of physical reasoning to the interpretation of actual current weather, and to forecasting practices. As a result of these efforts, it has become practicable during recent years to supplement the empirical methods of forecasting, as developed in the nineteenth century on the basis of experience alone, with procedures based on an understanding of the physical processes involved; and it is to this and closely related topics that the present paper will be restricted, although a number of other problems in which important developments are taking place could also be mentioned if space permitted.

The state of the weather is commonly specified by means of the six so-called meteorological elements, namely, air-temperature, barometric pressure, wind-direction and wind-speed, humidity, clouds, and precipitation; and the standard method of representing the weather-conditions over a given region at any particular time is by means of the familiar synoptic map. Now, the meteorological elements are completely determined by the temperature, pressure, density, and three velocity components of the air, and its total solid, liquid, and gaseous water-content; clearly, therefore, the weather is a dynamic and thermodynamic process, but formidable difficulties are encountered in attempting to develop and apply meteorology on this basis, particularly in the case of such problems as weather-forecasting. Even an empirical understanding of the storms and irregular weather-changes of temperate regions was slow to develop, but by the middle of the nineteenth century the empirical coordination of observational facts had progressed far enough to provide a fair, though incomplete, foundation for theoretical investigations; and shortly thereafter the pioneer work of William Ferrel inaugurated the development of theoretical meteorology on an exact physical basis. The first treatise to present meteorology from the dynamical point of view was the "Lehrbuch der Meteorologie" of A. Sprung, published in 1885. For a long period of time, however, the theoretical treatment was practically confined to the development of fundamental general principles, and to the discussion of the more regular large-scale features of atmospheric processes, or to particular phenomena considered separately from one another, usually on the assumption of more or less idealized circumstances; these investigations did not provide a solution to the practical problem of achieving a satisfactory theoretical representation of the current day-to-day weather which results from all the concurrent phenomena produced by the simultaneous action of the various factors in operation under actual conditions in the atmosphere. The synoptic map had been introduced into meteorology early in the nineteenth century by Brandes and Redfield; and after the invention of the electric telegraph it had come into daily use, for delineating and forecasting weather-conditions, among the national meteorological services that were established in the principal countries of the world soon after daily telegraphic charts were first regularly issued in France in 1863. The daily synoptic map has been a powerful aid to meteorological investigation, while weather-forecasting from these maps has rendered invaluable service ever since its inception about 1860; but progress has been relatively slow in the attempt to interpret synoptic charts in terms of the physical processes in operation, and in efforts to apply a physical analysis of the weather to the deduction of future developments by supplementing empirical rules with an explicit application of the physical laws to which the phenomena conform.

The difficulties arise partly from the complexity of the phenomena, and partly from a lack of adequate observational data. In particular, a complete understanding of the weather at the surface of the Earth is in general impossible without a knowledge of conditions aloft to fairly great heights in the free air. The systematic exploration of the upper atmosphere by means of kites and sounding-balloons was initiated during the closing years of the nineteenth century; but daily data could not be obtained and made available for current use until after the general introduction of pilot-balloon and airplane soundings. Only quite recently has any attempt at daily synoptic vertical cross-sections of the atmosphere been feasible; and the data still are inadequate at best.

A complete investigation of the weather-phenomena over a given region requires regular observations at fairly frequent intervals, from both the surface and the upper air, over a territory that extends far beyond the limits of the area under immediate consideration; a satisfactory understanding of the weather over the entire continental United States, for example, would necessitate adequate data for at least the region from the mid-Pacific Ocean to Bermuda and from northern Alaska, Canada, and Greenland to Mexico and the West Indies; and it would be desirable to extend this area over a still larger part of the Northern Hemisphere. This ideal is far from having yet been attained, and much remains to be learned as to how to interpret and apply even all the data that now are available; but during recent years, notable increases have been effected in the number of reporting stations, including ships at sea, and in the extent of territory covered by the observing network, as well as in the completeness and frequency of the observations; while steady progress has been made in utilizing the data effectively, from both the empirical and the physical viewpoints.

We may reasonably expect, not only that investigations designed to elucidate the physical mechanism of weather-phenomena will contribute toward a better understanding of these phenomena, but also that this increased understanding will lead to an increase in the precision, and an improvement in the accuracy, of forecasts, and will in addition have the further distinct advantage of making weather-forecasting somewhat less of an esoteric art. The potential practical benefits necessarily constitute one of the principal incentives to theoretical research on the part of an official meteorological service; and while it is essential neither to discount the intrinsic importance of every advance in our knowledge of atmospheric phenomena, nor to overlook the indirect or probable ultimate practical value of theoretical results which cannot immediately be adapted or directly applied to practical work, it is at the same time desirable to keep always in mind the requirements that a solution of a problem must meet to be applicable in practice. The unusual demands of practical meteorological work, together with the extraordinary complexity of the phenomena involved, make it peculiarly difficult to meet the needs of applied meteorology.

Granted adequate observational data, the ideal procedure would of course be to derive a set of exact equations from which the coming weather might be mathematically computed, in the same manner that, for example, the astronomer represents and predicts celestial phenomena. In theory, this suggestion is not so hopeless as may at first sight appear: It is comparatively easy to set up a system of mathematical equations which, like the differential equations of motion of the planets, implicitly provide a complete representation of the phenomena under consideration and which when solved yield explicit mathematical formulae for the latter. The equations which express the dynamical phenomena of the atmosphere are, it is true, seven in number, and six of these are complicated partial differential equations; it is therefore apparent that a general analytical solution, obtained by integrating the system, is as yet impossible, but a difficulty of this nature, while it may estop the abstract mathematician, presents no insuperable barrier to the applied mathematician intent on the solution of a particular concrete problem. One heroic attempt at such a direct solution of the problem has been made; L. F. Richardson, in a study published in 1922 [see 1 of "References" at end of paper], applied the calculus of finite differences to the numerical integration of the equations and the computation of an actual forecast of pressure, temperature, and winds six hours in advance, but aside from the fact that the calculations for only two stations required six weeks of arduous labor, the result was somewhat disappointingly in error, and this error was traced to the effect of unavoidable defects in the available observations of winds. A method of this nature is therefore not only impractical at present, but apparently also inherently inadequate. A theoretical solution of the problem, no matter how complete from an abstract mathematical viewpoint, must be one that will give satisfactory numerical results from data of the character usually available; and to be of value in daily meteorological practice, it must also, of course, be rapid and simple of application.

A more promising method of attack in the effort to achieve something that approaches an exact calculation of future conditions is to restrict the attempt to some one basic element. The primary importance of barometric pressure distribution in the determination of synoptic conditions has inspired several attempts at a theoretical analysis and calculation of surface-pressure changes.

Pressure is the most accurately observed of all meteorological elements, and, unlike most of the other elements, is not subject to appreciable local disturbances, although in practice serious difficulties are introduced by the necessity, for synoptic purposes, of reductions to sea-level or other common level. The fundamental principle that governs all pressure-changes is very simple--wherever the apparent weight of the overlying air-column increases, the barometric pressure rises, while where the apparent weight of the overlying column decreases, the pressure falls; but in general the physical processes which lead to these changes in weight result from the operation of numerous complex and interacting influences throughout the depth of the atmosphere. Differential equations of great interest may be obtained which if they could be integrated would provide in large part an explanation and prognosis of synoptic pressure-changes [2]; but it is difficult to obtain relations that appear to have immediate promise for practical purposes. With the aid of a number of simplifying assumptions, Exner has constructed a theory of the pressure-changes that would be produced by advection in the atmosphere alone; and on this theory he has based a graphical method of calculating, from the courses of the isobars and isotherms on the synoptic map, the approximate pressure-changes to be expected on any given occasion [3]. The solution is a much simplified and very imperfect one, although it apparently is adequate to reproduce the principal features of actually observed pressure-change maps with fair accuracy on most occasions; its application in practice is limited, however, by its incomplete character.

The preceding methods all are based on the *dynamical* theory of the phenomena, which has the inherent disadvantage of being so complex as in general to require the introduction of rather extensive simplifying assumptions if the problem is not to be impracticable. In the search for a more advantageous procedure, it has been found that a basis which in theory is surprisingly adequate for many immediate practical purposes, and at the same time both rigorous and simple, is provided by the entirely *kinematical* relation expressed by the hydrodynamic equation of continuity; and several attempts have been made to utilize this equation: Exner, for example, as long ago as 1902, pointed out how the future synoptic distribution of pressure and velocity might theoretically be deduced from current conditions with the aid of the equation of continuity; but Margules showed that for results obtained in this way to be significant, it would be necessary, even under favorable circumstances, that the current wind-speed be known to an accuracy of the order of 50 ft/hr, and the wind-direction to within the order of one minute of arc [4]. Even if observations with this precision were available, it is evident that quantities of the above orders of magnitude would have no synoptic significance. In practice, therefore, the equation of continuity cannot be used in any way similar to that described by Exner; but the possibility of developing serviceable methods based on kinematical rather than dynamical principles is suggested.

That an exact theory of only the kinematical aspect may be of great value is consistent with the recognized fundamental importance of the pressure-distribution, because it is the field of flow which is directly determined by the pressure-field, while other phenomena are more or less directly produced by or incident to the motions of the air; and during recent years, attention has been directed more and more to the air-streams themselves--their motions, extent, and physical properties, and the relations of weather-phenomena thereto--instead of being, as in the earlier days of synoptic meteorology, almost wholly concentrated on pressure-formations as such.

It is obvious that the circulation of the atmosphere is one of the principal immediate factors in the daily weather over the globe. Great difficulty has been encountered in attempting to obtain from observations of the winds a satisfactory knowledge of this circulation; but for the purposes of the present discussion, it is sufficient to recognize that the air-motions which make up the circulation of the atmosphere as a whole constitute a complex and ever-varying system of innumerable different currents by which great masses of air are transported from place to place over long distances. It has been more or less vaguely realized for over a century that on many occasions two such currents, markedly different in velocity and temperature, and sharply separated, may flow adjacent to each other and produce distinctive weather-phenomena as one succeeds the other at a given place; this idea was clearly expressed as early as 1828 by Dove, who ascribed the storms of temperate latitudes to conflicts between polar currents and equatorial currents. Only very limited observation is needed to reveal instances in which all of the meteorological elements change simultaneously and abruptly in a pronounced manner, as the boundary between two different currents sweeps over the observing station, the transition from one to the other amounting practically to an actual discontinuity. Such discontinuities frequently are quite conspicuous on synoptic charts; they have long been recognized by the forecaster, and were the subject of extensive theoretical investigations by Helmholtz and Margules. It was not until during the World War, however, that an intensive effort was made to investigate the separate currents in detail, explicitly as a basis for the interpretation of the phenomena shown on the daily maps. The investigation was initiated in Norway, under the leadership of V. Bjerknes, after the Scandinavian countries had ceased to receive meteorological data from other countries because of the war.

On very detailed surface-charts, prepared from unusually comprehensive observations at an exceedingly dense network of stations, it was found that a number of individual currents ordinarily could be identified and followed from day to day; they differed more or less from one another in direction of movement, speed, temperature, and other characteristics, and often ended abruptly against one another, with the clouds, precipitation, and other weather-phenomena definitely related to these discontinuities. A study of the maps revealed definite indications of the particular physical processes that accompany the interactions of adjacent polar and tropical currents; and led to the so-called Polar-Front Theory of the formation, structure, and development of cyclonic disturbances [5]--a theory which involves, with more or less modification and amplification, many ideas expressed earlier by Dove, Helmholtz, Margules, Blasius, Shaw, and others [6], and which in many respects is not inconsistent with other contemporary views, such as, for example, those of the Austrian school.

The further development of these ideas, and the elaboration, principally under the leadership of J. Bjerknes, T. Bergeron, and H. Solberg, of a systematic technique for the delimitation of the individual currents on the daily maps, have led to "air-mass analysis," to which so much prominence has been given in recent years: Over large areas of the Earth, especially in polar and in tropical regions, the meteorological conditions are so nearly uniform and steady, and the circulation so relatively weak and restricted for long periods that the atmosphere up to great heights above these areas takes on distinctive properties of temperature, moisture, and stability that are characteristic of the regions. Frequently an atmospheric current originates in one of these areas and transports large quantities of air to distant parts of the Earth. as, for example, when a great body of intensely cold air pours out from the Arctic and flows down over the globe to lower latitudes, sometimes covering the larger part of the North American Continent with its frigid winds. Moving masses of air from different localities tend as they travel to retain many of the initial physical properties characteristic of their respective source-regions, especially at upper levels, although of course they gradually become more and more modified as time goes on by the conditions encountered during their progress. When air-masses from widely separated places of origin, and with distinctly different properties, are brought into juxtaposition by the currents that are continually traversing the atmosphere, these bodies of air do not freely mix, but tend to retain their identity and to remain separated from one another throughout much of their history by more or less well-defined surfaces of discontinuity or sharp transition-zones in temperature, humidity, and velocity; until eventually, after profound modification by the long-continued action of external influences, they are subject to mixture, dissipation, and ultimate disappearance as separate bodies. It is at the interfaces where different air-masses meet, or so-called frontal surfaces, that the processes involved in weather-phenomena are in general most active, although many important phenomena also frequently take place within the body of an air-mass. In the analysis of synoptic maps, it is necessary to identify and delimit the separate air-masses, classify them according to source-region and characteristics [7], trace their movements and progressive modifications from day to day, and determine the associated physical processes and their relations to the attendant weather-phenomena [8].

The daily location of the fronts, or lines on the surface of the Earth which bound the different air-masses, presents a difficult problem in practice: The contrasts frequently are obscure, and may not exist in all of the physical properties. Success in the analysis requires that appropriate and adequate data be available to a trained and experienced personnel. In particular, a network of aerological soundings to fairly great heights is indispensable; and until upper-air data could be made quickly available by the introduction of airplane soundings, air-mass analysis could not receive extensive application in daily work. The current characteristics of an air-mass depend on both its source and the modifications it has undergone during its progress away from the source-region; these modifications, which tend to weaken the distinctions, are in general much more rapid and extensive near the surface of the Earth than aloft. Furthermore, surface-observations alone frequently do not reveal conditions and physical processes aloft that on many occasions are the principal cause of important phenomena at the surface, and without a knowledge of which the latter cannot be explained or foreseen. Among present tendencies in meteorology, one of the most important is the active effort to develop facilities for improving the adequacy of data and to devise effective means for their application in connection with the physical interpretation of synoptic maps.

The surface-charts are being improved by the inclusion of further data; recently, for example, in the United States, dew-points and 3-hour pressure tendencies have been added. Vertical cross-sections through the atmosphere, so far as they can be constructed from data now available, are supplementing the surface-map and the mere plots of upper-air data against height [9]. Efforts are being made to develop methods for obtaining aerological observations under all conditions and from a denser network; airplane-observations are too costly to be provided in large numbers, and are likely to be entirely lacking at critical times when the data are most needed. One of the most promising developments in this connection is the radio-meteorograph--a mechanism which is carried aloft by a small balloon, and by which pressure, temperature, and humidity are caused to actuate a short-wave radio transmitting apparatus that conveys a record to radio receiving apparatus on the ground; intensive experiments to design appropriate and inexpensive instruments are being conducted in many different countries [10].

A number of special procedures have been devised for putting the data, especially those from the upper air, into a form that will facilitate their effective and convenient application in practice, both for the identification of air-masses from place to place and time to time, and also for the purpose of analyzing the physical conditions and processes. Investigations for this purpose have in recent years led to an extensive development of the thermodynamical theory of atmospheric phenomena, and of practical means for applying it [11]. Some properties of the air are more conservative than others during the modification of an air-mass; in seeking an index which will remain as nearly as possible constant, the specific humidity and the equivalent potential temperature have been found especially useful and are now included in the daily telegraphic reports of aerological soundings in this country. The specific humidity is the mass of water-vapor per unit-mass of moist air; the equivalent potential temperature is the temperature that would result from a pseudoadiabatic lifting until all moisture was precipitated, followed by an adiabatic return to standard pressure. In developing methods for representing the data from a sounding in a form that will show the meteorological import of the physical conditions and be adapted to practical needs, a number of thermodynamic diagrams have been devised and have come into regular use; they include the adiabatic chart, the tephigram, the emagram, the Refsdal aerogram, and the Rossby diagram. The Rossby diagram is particularly useful for bringing out significant properties of the air; the sounding is plotted on a chart with the so-called mixing ratio (mass of water-vapor per unit-mass of dry air) as abscissa and potential temperature of the dry-air component of the atmosphere as ordinate, and with networks of lines showing equivalent potential temperatures, and isobars and isotherms for the condensation level, as background.

It is evident that the value of air-mass analysis for forecasting purposes would be greatly enhanced if quantitative methods based on rigorous physical theory could be made available by which the movements of fronts and air-masses might be reliably calculated. Some attempts have been made to develop a dynamical theory of the motions of air-streams over the Earth [12], but the results obtained so far are not satisfactory even for theoretical purposes. More recently, Angervo and Gião have investigated the theoretical calculation of the motions of fronts and pressure-systems [13] by more practicable methods; but the most comprehensive and practically promising investigations are those by Sverre Petterssen [14], of the Norwegian Meteorological Service, which include some reference to the work of Angervo and Gião. On the basis of the kinematical theory of fluid motion, Petterssen has developed rigorous methods for a kinematical analysis of the synoptic chart in conjunction with the frontal analysis, and has derived methods for calculating the movements, transformations, and developments of pressure-formations and fronts. Experience has shown these methods to be entirely practicable, and capable of giving good results.

In the foregoing outline, an attempt has been made to show that an ultimately satisfactory solution to the problem presented by weather-phenomena and their prediction involves: (1) The development of sound and adequate theories, on the basis of mathematical physics, which shall be capable of leading to results that may be adapted to the needs of practical meteorological work; (2) the collection, and the reduction and analysis on the basis of physical principles, of appropriate and adequate data from the surface and the upper air over a wide territory; (3) the practical utilization of the theoretical principles and the observational data, which involves (a) the construction of accurate synoptic maps and vertical cross-sections, and their physical analysis by frontal, kinematical, and thermodynamic methods, and (b) the determination of the displacements, transformations, and developments that are indicated on the synoptic map, and a forecast of the weather-conditions that will accompany them. It must be recognized that the physical analysis of the map is quite distinct from the making of a forecast; it is the difficult step from analysis to forecast that is especially facilitated by methods such as those of Petterssen.

The recent contributions which have been referred to in the present report are being actively studied and tested in the meteorological services of the United States and other countries. Many of them have proved to be of inestimable value, although further investigation and more experience is needed before their application in actual forecasting is fully developed and understood. Under the influence of these recent developments, weather-forecasting, at first exclusively empirical, is now developing along sound physical lines [15]; but for a long time to come, forecasting must continue to be a combination of physical reasoning with methods based on accumulated practical experience with synoptic charts. We cannot now, and may never, safely do without the empirical judgment of the experienced forecaster.

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U. S. Weather Bureau,
Washington, D. C.

RESOLUTIONS ADOPTED

(I) RESOLUTION ON THE DEATH OF ARTHUR J. WEED

WHEREAS, In the death of Arthur J. Weed on April 15, 1936, the American Geophysical Union lost a member who has long been active in the field of instrumental seismology and in the affairs of the Section of Seismology, and

WHEREAS, Mr. Weed made notable contributions to seismology in the design and construction of both teleseismic and strong-motion seismographs, adding materially to the technique of constructing mechanical recorders, and

WHEREAS, He was largely responsible for the establishment and maintenance of the teleseismic station at the University of Virginia,

RESOLVED, That the American Geophysical Union express its sense of great loss through the death of this faithful member, and be it further

RESOLVED, That a copy of this resolution be sent to Mr. Weed's family and to the President of the University of Virginia.

(II) RESOLUTION ON THE DEATH OF ROY JED COLONY

WHEREAS, In the death of Roy Jed Colony on March 26, 1936, the American Geophysical Union lost a member long active in the field of petrology, and

WHEREAS, In addition to being a most inspiring teacher of petrology, Professor Colony made notable contributions in the interpretation of features of igneous rocks and in particular to the phenomena of final consolidation in crystallization of igneous rocks, and

WHEREAS, He advanced the application of petrology to study of cement and to engineering and industrial problems, together with contributions to the knowledge of magnetite-ore deposits, therefore be it

RESOLVED, That the American Geophysical Union express its sense of great loss through his death, and be it further

RESOLVED, That copies of this resolution be sent to Professor Colony's family and to the President of Columbia University.

(III) RESOLUTION ON THE DEATH OF EDWIN JAY BROWN

WHEREAS, In the death on June 17, 1935, of Lieutenant Edwin Jay Brown of the United States Coast and Geodetic Survey the science of Geodesy has lost a man who, in spite of his comparative youth, had already made notable contributions to geodesy and gave promise of further achievement, and

WHEREAS, Lieutenant Brown had devised a form of gravity-apparatus bearing his name, in recognition of the part he played in perfecting it, which increased the speed of gravity-determinations three or four hundred per cent without loss of accuracy, and had designed various other devices used in determinations of time or gravity, and

WHEREAS, He had been assigned to important geodetic operations, including observations in Hawaii for the radio longitude-net of 1926 and the gravity-connection between Washington and Potsdam, of fundamental importance for gravity-work in the United States and for the determination of certain physical quantities and had performed these operations, as he performed his other duties, with skill and fidelity, and

WHEREAS, His genial and upright character endeared him to his friends and associates, therefore be it

RESOLVED, That the American Geophysical Union hereby express and place on record its sense of loss by the death of Edwin Jay Brown, and be it further

RESOLVED, That copies of this resolution be transmitted to his widow, to his mother, and to the Director of the United States Coast and Geodetic Survey.

(IV) RESOLUTION ON THE DEATH OF CHRISTIAN HUFF

WHEREAS, In the death of Christian Huff on January 14, 1936, the American Geophysical Union has lost an active worker in the field of terrestrial magnetism and electricity, and

WHEREAS, He rendered notable service to geophysics through the active part taken in the design and construction of instruments used by field-parties, at observatories, and on board the Carnegie, therefore be it

RESOLVED, That the American Geophysical Union express its sense of great loss through his death, and be it further

RESOLVED, That a copy of this resolution be sent to Mr. Huff's family.

(V) RESOLUTION ON THE DEATH OF VERYL R. FULLER

WHEREAS, In the death of Veryl R. Fuller on May 30, 1935, the American Geophysical Union has lost a member who has long been active in the field of terrestrial magnetism, and

WHEREAS, He made important series of auroral observations and studies at the University of Alaska, College, Alaska, preceding, during, and following the Second International Polar Year 1932-33, therefore be it

RESOLVED, That the American Geophysical Union express its sense of great loss through his death, and be it further

RESOLVED, That a copy of this resolution be sent to Professor Fuller's family and to the President of the University of Alaska.

(VI) RESOLUTION ON TOPOGRAPHIC MAPPING

WHEREAS, In practically all phases of geophysical research a knowledge of the terrain is essential, and

WHEREAS, The best modern topographic maps show the terrain in such detail and with such accuracy as is needed for research in geophysics, either for scientific or for commercial purposes, and

WHEREAS, Good topographic maps are of very great value, in operations connected with waterpower and soil-conservation and in other engineering operations, therefore be it

RESOLVED, That the American Geophysical Union recommend and urge that the Federal Government complete the topographic mapping of this country in as short a time as practicable, and be it further

RESOLVED, That copies of this resolution be sent to the President of the United States, to the President of the Senate, to the Speaker of the House of Representatives, and to other government officials who would either be concerned in carrying on the topographic mapping or who would benefit by its completion.

(VII) RESOLUTION ON NAVAL OBSERVATORY TIME-SIGNALS

WHEREAS, Accurate radio time-signals which are now being broadcast by the United States Naval Observatory twenty times daily on a certain frequency and many times daily on other frequencies are essential for seismological and geodetic investigations of special or routine character, and

WHEREAS, A published notice in the Hydrographic Bulletin states that the 690-kilocycle time-signal from NAL is to be discontinued on June 1, 1936, a signal which is of special value to many seismologists in the eastern part of the United States, therefore be it

RESOLVED, That the American Geophysical Union in joint assembly express the greatest appreciation and gratitude for this excellent time-service, and be it further

RESOLVED, That every reasonable effort be made by the Naval Observatory staff to continue the present schedule of time-signal broadcasts (including the 690-kilocycle signal) and, if possible, to increase it, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the Navy, to the Chief of the Bureau of Navigation, United States Navy, and to the Superintendent of the United States Naval Observatory.

(VIII) RESOLUTION ON FORMS FOR RECORDING OCEANOGRAPHIC OBSERVATIONS

WHEREAS, It is necessary to have appropriate forms on which to record oceanographic observations made at sea and data pertinent thereto, and

WHEREAS, There is at present much diversity in the forms used by different organizations, and

WHEREAS, It is desirable to have definite forms adopted for use by different institutions engaged in oceanographic work, therefore be it

RESOLVED, That the American Geophysical Union authorize the Section of Oceanography to appoint a Committee to study the problem of forms to be used in recording oceanographic observations at sea and to submit recommendations at the annual meeting of this Section in 1937, and that this Committee be composed of one representative each from the Hydrographic Office of the Navy, the United States Coast and Geodetic Survey, the United States Bureau of Fisheries, the Woods Hole Oceanographic Institution, the Bingham Oceanograpnic Foundation of Yale University, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the Oceanographic Laboratories of the University of Washington, the Scripps Institution of Oceanography of the University of California, and from such other institutions as should properly be included.

(IX) RESOLUTION ON EXTENSION OF HYDROGRAPHIC SURVEYS

WHEREAS, With improved methods of marine surveying developed during the past few years there has been demonstrated the existence of an intricate topography on the floor of the ocean, and

WHEREAS, The extension and amplification of this record requires not only that the zone of the surveys be extended to a greater distance seaward but also that these offshore surveys be carried out in greater detail, and

WHEREAS, The results secured in the last few years show that such surveys will give data of fundamental importance in the interpretation of the history of the Earth, the distribution of animals and plants, and, in fact, all branches of natural science, and

WHEREAS, The increasing use of echo-sounding equipment by the merchant marine makes the charted results of these surveys of value to commerce, therefore be it

RESOLVED, That the American Geophysical Union express its hearty appreciation and approval of the work done along this line by all agencies engaged therein, and also its earnest hope that means may be found not only to continue but also greatly to extend it, and be it further

RESOLVED, That copies of this resolution be sent to the secretaries of the governmental departments concerned.

AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

SECTION OF GEODESY

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STATE GEODETIC CONTROL-SURVEYS

H. W. Hemple

During the fall of 1933 the Coast and Geodetic Survey initiated a project in each State under the Civil Works Administration for the establishment of lines of surveying monuments at a closer spacing than pertains to the regular program of surveys conducted with its own field force. These surveying monuments are located geodetically and serve as control-stations for mapping and local surveying uses. Any maps or surveys adequately tied into such control-survey monuments will bear a true relationship to each other.

The project as originally initiated provided that any engineer out of work might be employed thereon. This was the criterion governing employment during the time the project was under our jurisdiction and for a short period thereafter. On February 15, 1934, when Congress passed a bill providing that no Civil Works Administration projects were to be conducted by the older established Federal bureaus, there were in excess of 10,000 employees on this project, about 5,000 of whom were professional engineers. Since this date the work has been carried on in several states, first under the State Civil Works Administration, later under the State Emergency Relief Administration, and now under the State Works Progress Administration.

These State projects are now sponsored by organizations within each State, such as State Highway Departments, State Public Works Commissions, State Conservation Commissions, State Universities, etc. The work is under the direction of an outstanding engineer who must be a citizen of the State. Many of these men are professors of engineering in the leading engineering schools, and act as consultants and directors on the project, devoting but part of their time to administrative duties. Supervising engineers, selected from non-relief sources, and paid higher salaries than accorded those employees obtained from relief rolls, have direct charge of the work.

The criterion for employment at present is that all but ten per cent of those employed must be selected from men who have been on relief rolls. In special instances where the project cannot be successfully conducted under this restriction, the State Administrator may allow 25 per cent or even more to be employed from non-relief sources. At the present time such projects are conducted in 14 states, with the number employed being approximately 2,000, ranging from 7 in New Hampshire to 400 in Louisiana and 440 in Massachusetts.

The connection of the Coast and Geodetic Survey with such projects under the present situation is to act in an advisory capacity, when so requested by the State Director. We cannot initiate or sponsor these surveys, because of lack of authority to do so. We are permitted to furnish computing forms which cannot be obtained elsewhere to the various State organizations. In return the data concerning these surveys are being furnished to our office for inclusion in the national net of control-surveys.

The surveys are being conducted under specifications issued by this Bureau providing for second-order accuracy. The instruments used are those generally available to the ordinary surveyor or engineer.

Most of the horizontal control consists of traverse surveying, although some triangulation has also been accomplished. The traverse measurements are made along highways, or the right-of-ways of railroads. One-hundred-foot steel tapes are used and the tape is either supported throughout, as along the track of a railroad, or supported only at the two ends on portable tripod bucks. Differences of elevation of the ends of the tape are obtained either with a clinometer or by means of instrumental leveling. A definite tension is applied to the tape and a temperature-reading is obtained at each tape-length. The field tape is compared frequently with a master-tape, which has been standardized at the National Bureau of Standards. Stations are established at not more than two-mile intervals. These stations are concrete monuments in each of which is set an inscribed metal tablet. An azimuth is determined at each station either to an object nearby, such as a water tank, church steeple, or if none such is visible, to a concrete azimuth-mark at least 1/4 mile distant established for this purpose. Taping is conducted in both a forward and backward direction. Corrections to the tape-lengths are applied for standardization, temperature, and grade.

Angles are measured with the best instrument available, which usually is a transit reading to the nearest minute or at best to 30 seconds. These observations consist of a measurement of an angle by six repetitions of the angle with the telescope in the direct position, followed immediately by six measurements of the explement of the angle with the telescope in the reverse position. Each angle at the station is thus measured, and such observations comprise one set. For work of the accuracy required for these traverses at least two sets, and in some cases three or four, are necessary. Angles should agree within eight seconds of the mean, or the observations are repeated. The azimuths are carried through as long lines as possible, so that the error from this source may be kept as small as possible. While the instructions call for the establishment of stations at not more than two-mile distances, the condition of the terrain may be such that the controlling azimuth can be carried past several stations by means of lines of sight from five to ten miles in length. This procedure is followed wherever possible, and adds to the accuracy of the work.

Traverse lines are run between triangulation-stations established by the United States Coast and Geodetic Survey. The positions of these stations are now expressed in terms of plane as well as geographic coordinates. The computations of the field-data follow the ordinary procedure for plane-surveying practice, and the final positions of the traverse monuments are expressed in terms of the State plane-coordinate system. The traverse closures must be of second-order accuracy of 1:10,000 or better. If the specifications are rigidly followed, no difficulty is experienced in obtaining results of such accuracy. For example, in Massachusetts 138 traverse lines have been completed, the average closure being 1:24,100. The mileage for these traverses amounts to 1,640 in this State, and it has been necessary to re-run 122 miles or 7.5 per cent. In Louisiana, the average closure for traverse is 1:35,000, for leveling it is 0.03 foot $\sqrt{\text{distance in miles}}$. About 1,500 miles of traverse and leveling have been completed in this State. Equally accurate work is being carried on in other states.

The leveling work is run over the monuments located by the traverse. The ordinary wye- or dumpy-level, with the Philadelphia self-reading rod, is used. One running of the line is required and the check, obtained on the first or second-order bench-mark to which connections are made, must be of third-order accuracy as expressed by the formula, 0.05 foot $\sqrt{\text{distance in miles}}$. The specifications call for backsights and foresights of equal length, turning points carefully chosen, stable set-up of instrument, etc. No difficulty nas been experienced in obtaining leveling of the required accuracy.

Each party consists of a chief of party, transit man, levelmen, and seven assistants such as chainmen and rodmen. Traverse and leveling are carried on concurrently. Since the wages paid are relatively low, it is necessary that the men live at home, in order that they may not be subject to unusual living expenses. This requires that the field-work be accomplished within short distances of urban centers, where the unemployed are largely located.

In so far as possible the computations effecting these surveys are completed in computing offices in the respective states. The field-notes, descriptions of stations, and completed computations are forwarded to the Washington office of the United States Coast and Geodetic Survey. If such work is satisfactory, and the various criterions of accuracy are adhered to, the results are accepted. In any future publications concerning control-data for such states, the work done by the State organizations will be included.

To date in excess of 40,000 miles of traverse and a like amount of leveling have been accomplished by these State organizations. The final adjustment of much of this work has not yet been completed, since a great deal of it is connected to fundamental first-order arcs which have not yet been adjusted. Some of these adjustments are held in abeyance pending the completion of field-work on additional arcs, so that the positions of the necessary junction-points can be established. It is hoped that eventually all the work done by the State Survey organizations will have adequate connections and the final determinations of positions and elevations may be obtained.

Among the benefits resulting from the State geodetic surveys may be mentioned the following:

From an altruistic standpoint these projects have furnished work to many of the engineering profession, who through no fault of their own have been released from industrial employment. Many such engineers have been forced to accept employment during the depression at whatever type of work they could obtain. Those employed on these survey-projects have felt that they were engaged on work for which their technical training fitted them, and their morale has consequently been higher than those who found it necessary to accept employment on other than engineering projects. The project lends itself readily to the relief of idle engineers, and has been valuable in relieving an acute situation in unemployment among this class of professional men.

From a practical viewpoint there have been added to the national net of control-surveys in excess of 40,000 miles. Most of this mileage is supplemental to the fundamental network on which the regular program of the Coast and Geodetic Survey is concentrated. In any large-scale mapping program, the data concerning these supplemental surveys can be used and will make unnecessary further detailed control-surveys in the localities where such field-work has been adequately accomplished.

As a result of these surveys, plane-coordinate systems have been adopted for the States. Previous to the fall of 1933 geodetic data were expressed in geographic coordinates. In order to use such information in connection with local surveys, a knowledge of geodetic computing is necessary. These data were not in as general use as they should have been, because engineers and surveyors commonly think that such computations are abstruse and time-consuming. Expressing such data on the State plane-coordinate systems makes it possible for the engineer and surveyor to adapt such information to his use and compute his surveys by the methods of plane surveying with which he is familiar. A more wide-spread use of data concerning control-stations is resulting.

A law has recently been promulgated in New Jersey legalizing the use of the State plane-coordinate system for property description. Movements are taking place in other states to place similar laws on their statute-books. The effects of such a law are far-reaching, and will concern all holders of real estate. When property corners are generally expressed in terms of plane coordinates resulting from accurate surveys, suits regarding questions of boundary-demarcation and location will be considerably reduced in number over those which now are or have been in process of adjudication. The passage of such a law in New Jersey resulted directly from the initiative and interest of engineers and surveyors, who have been administering or closely connected with the State geodetic surveys. Similarly in other states, interest in the passage of such a law manifests itself among those who have been connected with the State survey-projects.

The engineers and surveyors who have been employed on the State geodetic survey-projects have become familiar with the methods of conducting accurate surveys. Should these men be called on in the future to do surveying for their own purpose, or that of private organizations, they can incorporate such methods in the field-procedure, and a large amount of accurate surveying data will result. If the notes regarding such surveys are made generally available through a central survey-and-map office in each State, much of the repetition of surveys over the same ground which now is found necessary will be obviated.

These engineers now realize that it is possible to do accurate surveying with the instruments generally available. They also understand that such surveying can be done more efficiently and economically with instruments of greater refinement. I believe that gradually better instruments will come into more general use. If such instruments were manufactured in this country, and made available at lower costs due to quantity production, I think there would be a demand for them, possibly greater than anticipated by the instrument-makers.

The last few years have witnessed a renaissance in surveying and mapping. Several factors have contributed to this increased interest. The many engineering problems in connection with studies for flood-control, water-power developments, and other large projects have focused the attention of the Nation on the lack of maps by means of which comprehensive and accurate studies of the contemplated large-scale works can be made. The enlarged program of control-surveys on which the regular forces of the Coast and Geodetic Survey operated during the years 1932 to 1935 has also brought surveying to the fore. The State control-projects, however, in my opinion, have been the largest factor contributing to the increased interest in surveying and mapping. Many of the men who have been engaged on such work have taken part in the persistent efforts now being made to have the Congress adopt a Federal program and provide funds to complete the mapping of this country.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GUATEMALA-HONDURAS BOUNDARY

Joseph P. Lushene

In September, 1821, the Spanish Colony now known as Central America declared its independence from Spain and formed the republics of Guatemala, El Salvador, Honduras, Nicaragua, and Costa Rica. The area was largely an unexplored jungle and included only a few isolated and scattered settlements. The boundaries and limits were very vague, as the prime purpose was independence from Spain. In a short time the natural resources of the republics resulted in a

FIG. 1—ASTRONOMIC SET-UP AT STATION ESKIMO

FIG. 2—PLANE USED TO TRANSPORT ASTRONOMIC EQUIPMENT

large number of settlements. When settlements became numerous and many valuable minerals were found, boundary-disputes arose between adjacent countries. These led to litigation and resulted in much confusion and expenditure of money.

Many attempts were made at various times to settle the dispute between Guatemala and Honduras with very little being actually accomplished. Finally, in July 1930, a treaty was signed and a Special Boundary Tribunal set up which consisted of the Chief Justice of the United States Supreme Court, an arbitrator from Costa Rica, and one from Chile. An aerial map of the territory in dispute was made which proved to be almost indispensable in determining the final award and in the later reconnaissance-work. Guatemala and Honduras each felt that they had gained considerably by the award as made by the Special Boundary Tribunal. The tenseness between the two countries immediately disappeared. In order to prevent a recurrence of trouble it was necessary to mark the boundary-line permanently and therefore a Technical Commission was formed for the demarcation. The determination of positions of the boundary-points called for the most accurate method known, that of first-order triangulation. The Director of the United States Coast and Geodetic Survey was requested to cooperate by sending an observer to make accurate determinations of the important and vital points. The writer was very fortunate in being detailed to undertake these control-surveys.

When boundary-points are to be designated by latitude and longitude, triangulation is the most scientific and accurate method known for determining the coordinates. Latitudes and longitudes determined by astronomical means alone are inadequate and unsatisfactory as they are affected by deflections of the vertical. As no triangulation existed in this locality it was necessary to derive certain fundamental data for this survey and for others that might be carried out in the future. Bases, astronomical determinations, and a starting datum were needed. A base was measured and determinations of latitude, longitude, and azimuth were made at one of the stations near the northern end of the arc where transportation of the heavy instruments was not difficult. This provided the necessary basic data for the establishment of the arc of triangulation along the boundary. The positions of the points determined by triangulation could then be derived when the triangulation was connected to this astronomical station.

The Commissioners of Honduras requested that a second astronomical determination be made at the southern end of the arc in order to provide Honduras with an astronomical station for future use in that Republic. The matter of establishing a second station was a serious problem because of the lack of facilities for transportation. The equipment for astronomical work is very heavy and bulky and cannot be transported satisfactorily by mules over poor trails. The problem was solved by chartering an airplane. The plane picked up the equipment at the most southern railroad terminal and landed it in a pasture near the station at the southern end of the boundary where the observations were desired. The trip by plane was made in about 25 minutes, whereas it would probably have taken a week for transportation by mule. Although transportation by plane for geodetic operations is quite unusual, it will probably play an important part in future geodetic work.

With astronomical determinations at each end of the arc it was possible to compute a temporary datum for the triangulation which was undoubtedly more accurate than could be obtained from a single astronomical station. The comparison of the astronomical data with the geodetic data derived from preliminary field-computations indicated a relative deflection of about 13" in latitude and 11"5 in longitude between the two astronomical stations. The topography is so rough immediately around each of the stations that the theoretical values of the deflection could not be computed with any assurance of accuracy, especially as accurate contour-maps were not available. It was even impossible to tell which of the two stations was less affected by deflections of the vertical and for this reason the total discrepancy for the arc of triangulation was equally divided between the two ends of the arc. The azimuth discrepancy from one end of the arc to the other as derived by a Laplace equation was 3"97, which indicated that very little twist existed in the triangulation.

With first-order bases and a satisfactory datum available the process of determining the positions of the boundary-monuments to meet the rigid requirements of the Boundary Commission was merely a matter of accurate triangulation, that is, triangulation having satisfactory angle- and length-closures. The arc of triangulation was made to straddle the boundary-line wherever possible. The boundary-line is 161 miles long; it follows water-courses and water-divides, and in some sections consists of straight lines from one topographic feature to another. In general, the line passes through highly mountainous country. The northern part of the line extends through a sparsely inhabited region which is heavily timbered with tropical growth. There are practically no trails in this area and the few trails that were found were very poor and practically impassable over the long rainy season. Parts of the area are absolutely uninhabited. Most of the traveling in this region was done afoot with natives carrying the equipment, supplies, and food. Trails were cut through the jungle growth to all the stations, and station sites were cleared of trees. To permit visibility a large number of trees had to be cut ranging from 100 to 175 feet in height and from 3 to 5 feet in diameter. In the lowlands and enroute to the stations the temperature was extremely hot and uncomfortable for back-packing, but at the stations themselves it was cold and heavy woolen clothing was needed. The southern part of the arc passed through country very much different from that of the northern part. The growth is not tropical but chiefly pines; the region is well settled and has numerous trails. In many cases direct access to the station was possible. Most of the traveling was done on mule back, the supplies being transported by pack-mules.

The instruments used on the work were a Parkhurst theodolite of latest design and a Bausch and Lomb 10-inch theodolite. These two instruments were fitted with circles graduated by the National Bureau of Standards. These accurately graduated circles aided materially in the progress of the work. A theodolite is useless without a good circle and the National Bureau of Standards is to be commended upon the precision of their work on circles. On only two stations were observations repeated because of slightly large closures. Of the two instruments the Parkhurst seemed to be a favorite with the natives, as the weight of this instrument is about one-half of that of the other type. It was extremely difficult to find men to pack the heavier instrument up the mountains. The Parkhurst theodolite is undoubtedly the ideal type for mountain work because of both its high accuracy and its portability.

The triangulation was begun at the southern end because of the heavy rains in the northern part. During the first few weeks the work progressed rather slowly due to the inexperience of the lightkeepers. Much time was spent in training the personnel in the care and handling of lights, including focusing and plumbing. English was not understood by the men and it was necessary to arrange special codes and signals for communication purposes between stations. Each lightkeeper was given an assistant who served as a cook, cargo-man, and companion. Much time was saved by this procedure for in many instances the assistant became lightkeeper when the health of the lightkeeper failed. Illness seemed to be quite prevalent, with malaria and dysentery the chief ailments.

The respective governments desired that the work be completed at the earliest possible date, and since there were only two to three months during which the weather would be suitable it was necessary to carry on the work with a double observing unit. The late Philip L. Welker, a former computer of the United States Coast and Geodetic Survey Office, was in charge of the observing unit in Guatemala and the writer had the one in Honduras. Four-foot stands were high enough at most of the stations since the reconnaissance-party had cleared the heavy growth on all high mountains. A 15- to 20-foot tripod was placed over each stand. Each tripod carried a banner so that vertical angles could be taken during the day when refraction was at a minimum. The tripod also served as a stand for the light to be shown the observer on the opposite side of the scheme and it also made an excellent frame for a wind-break for the theodolite.

The greatest delay to the observing party was caused by cloudy weather which kept most of the stations in the clouds for long periods of time. On several occasions observations were made above the clouds. Usually after midnight the heavy clouds would settle into the valleys and observations could be made above them. Large tripods painted white were set over the boundary-monuments, and during the day six to eight directions were taken on all of these that were visible and positions were computed to control the work of the traverse party surveying the actual boundary. Thirty first-order triangulation-points were occupied and some 33 secondary points determined along the actual boundary. Severe field-conditions were encountered throughout the work; at the majority of stations ten or more days were required to complete the observations.

The difficult working conditions took their toll in the life of my very able assistant and friend, the late Philip L. Welker. At this time I wish to pay tribute to his splendid cooperation and expert services during the work.

The actual boundary-line was measured with transit and stadia, solar observations being used for azimuth-control. A vista was opened along the sections that were not marked by water-courses or other natural demarcations. On the boundary-line, two engineers, one from each country, were assigned to a transit party. Each engineer was directly responsible to the Chief of the Commission. He made a record of his measurements and was required to compare his results with his colleague. Certain limits of error were allowed and when observations failed to come within the limits, the observations were repeated. When two observations were closely enough in accord, the average of the two were accepted as final. At frequent intervals, points were located by intersection from the first-order stations to control the measurements of the local engineers.

The 48 triangles along the first-order arc had an average closure of 0".90 and the length-closure on the base was approximately 1 part in 200,000. Scientific methods and accurate instruments make this boundary-survey a lasting tribute to the foresight of the officials of Guatemala and Honduras. No further dispute or confusion should result, for if the marks or monuments are destroyed, maliciously or otherwise, the proper restoration can be made with very little labor. The work was carried on with a high degree of accuracy and afforded a means of training engineers in first-order triangulation for the first time in Central America. Since the arc extends more than two-thirds of the distance between the Atlantic and Pacific oceans, it makes an ideal base for future extensions of first-order triangulation in that territory. It is hoped that this arc of triangulation will eventually be connected with the precise triangulation-net of Mexico, and that it will be extended southward to Panama, thus giving Central America the North American Datum for control. A gratifying result of this arc of triangulation is that Central America has become geodetic-minded and much activity along this line can be looked for in the future.

U. S. Coast and Geodetic Survey,
Washington, D. C.

USE OF COLOR-FILTERS ON GEODETIC INSTRUMENTS

H. C. Warwick

For several years the United States Coast and Geodetic Survey has carried on intermittently a series of experiments with color-filters on first- and second-order theodolites and first-order levels in an attempt to improve the appearance of the object pointed upon by eliminating as far as possible the disturbances caused by heat-radiation and scattering light. It is consistent with Huyghen's theory that the red and yellow filters are found to be the best for absorbing the disturbing lights of the short-wave length, namely, those approaching the ultra-violet part of the spectrum.

Investigation along this line has given not only interesting and conclusive proofs, but also some more or less conflicting results. It is believed that the installation of the filter on the precise level is a benefit to the observer, and, as this is the simpler of the two phases, it will be considered first.

Some time ago, we started experimenting by running a series of short-loop closures with various types and colors of filters under different atmospheric conditions. In comparison with the length of sights on triangulation, and generally on traverse, the length of a level-sight is short. The maximum length of these sights under the most favorable conditions, according to the specifications of the United States Coast and Geodetic Survey for leveling, does not exceed 150 meters. On cloudy or overcast days, and even in a light rain, when the atmosphere is clear and still, filters are not found to be an advantage but rather a hindrance as they absorb too much of the needed light. In bright sunlight, however, the "boiling" caused by heat-radiation and the presence of scattering light of the short wave-length makes observing difficult, and we find that the filters are a decided help.

After trial of the various shades of glass filters, it was determined that a red filter, equivalent to the Eastman Kodak Company's Wratten No. 26, Stereo Red, was the best for general use. Possibly other shades would be better under various conditions, but as it is not practicable to equip an instrument with many shades, it was found that the glass referred to seemed to fit all conditions more satisfactorily than any other. This filter is installed at the eye-end of the level-telescope; no error from this source is introduced into the observations when it is fitted in this position.

A remarkable change in the appearance of the rod when the filter was in place was noted immediately when observing in strong sunlight. The contrast between the black and white on the invar strip appeared more pronounced, and to some extent the "boiling" caused by heat-waves diminished. The short-loop closures were run with and without the filter under identical conditions by the same observer, with the same lengths of sight and within a short time of each other. It was found that the closures were uniformly better when the filter was used.

The consensus of the various observers using the filters on actual field-work is that the filters will make it possible to increase the maximum length of sight about 20 per cent on days when heat-radiation is prevalent. Obviously, this will add appreciably to the efficiency of a leveling party.

The use of filters on theodolites or telescopes for longer sights is a more difficult problem. From my own observations and from those made by others, there is conflicting opinion. Observations with a theodolite are made under many conditions. Each line of sight at a single station may differ greatly from the others, and, while one shade of filter may improve vision under one or more conditions, we have not proved that any one color is generally better than another in all cases. It is believed that a light amber shade, corresponding to Eastman Kodak Company's Wratten Filter No. 8, K-2 orthochromatic, probably will best fit most observing conditions to be encountered, and for lack of knowledge of a better one this is being installed on a number of our theodolites at present.

Naturally it is not practicable for an observer on triangulation, traverse, or reconnaissance to equip himself with a dozen or more filters for trial at each station in order to determine which is most suitable for the particular conditions under which he is observing. These conditions are controlled by such factors as the character of the atmosphere, whether cloudy, bright sunlight, blue haze, smoke, or dust. The angle the line of sight bears to the Sun and the character of the terrain over which it passes also affect the vision.

Another interesting feature relating to conditions encountered is brought out by the characteristics of the individual eye. This was discovered a short time ago while observing with various shades of filters from the roof of the Commerce Building in Washington. The morning had been spent observing at different angles from the Sun using a number of filters from a book of Eastman Kodak Company's Wratten gelatin filters, consisting of 60 shades. Several field-engineers interested in the procedure were asked to make some observations. There were present three light-eyed and three dark-eyed men. By chance it was learned that, whereas the darker shade of filter assisted the men with light eyes to see the object pointed on more clearly, the light shade was of more assistance to the men with dark eyes. An impromptu discussion of this fact led me to consult with an eye specialist on this question. He substantiated what we had suspicioned, namely, that light eyes are generally more sensitive to light than dark eyes, varying from the albino who has no pigment and invariably suffers from a distress known to the medical profession as photophobia, to the native of the tropical countries whose eyes are constantly subjected to bright sunlight with no resulting ill effects.

Some time ago a light amber and a red filter were sent to the field to each of several triangulation-parties for trial. Reports from these parties using the filters, both in daylight and at night on observations on signal-lamps, indicate that the amber color is in some cases beneficial. None of these reports favored the darker red. One officer stated that when observing on natural and artificial objects during the day, these objects were brought out and defined more clearly when using the amber filter. It is not expected that the filters will greatly improve visibility at night when there is no sunlight to be filtered out and the only source of light is the object pointed on. However, one officer stated that the amber filter apparently reduced the flare from a flaring light. Another remarked that when pointing on lights before dark, the light was reduced to a fine yellow pinpoint, extremely pleasing to point on. One officer occupied four stations of a quadrilateral at night by alternately taking four of the 16 positions with the amber filter and then four without it. He closed the triangles with observations made under both conditions, and found the closures when using the filter were consistently better, not to any great extent, but in some cases possibly enough to cause a triangle to close within the required limit, when otherwise it would not have done so.

In addition to the application of filters to theodolites there is yet the possibility of using monochromatic light at the source for triangulation-signals at night. This is, so far as is known, an unexplored field.

The use of filters on reconnaissance-instruments should prove of benefit to the observer. Reconnaissance-engineers should be given a somewhat wider choice of colors than other observers. The nature of his work may be placed in the experimental class and it is essential that he be equipped with every possible means for improving visibility. It is a well-known fact that a camera equipped with a fast lens and an infra-red filter will record, on material having a high degree of sensitivity to infra-red light, objects invisible to the unaided eye. It does not follow, however, that when the eye replaces the sensitized plate the very long-wave filter is of especial advantage. However, it has been observed that when the distant horizon is viewed through a filter (the shade of the filter depending somewhat upon existing atmospheric conditions) the various ridges will stand out more clearly than when no filter is used. J. H. Churchill of the Nigerian Survey Department in one of his several articles on this subject appearing in the Empire Survey Review speaks of using the tinted cover-glass of his eight-power Zeiss binoculars for this purpose. Mr. Churchill's statement is somewhat as follows: The day was fine and sunny, but there was a faint haze which limited visibility to 50 miles. He set up his theodolite and searched the horizon in vain for a hill known to exist 65 miles distant. He also failed to distinguish the hill with the unaided eye, but when he used the binoculars equipped with tinted cover-glass he saw the hill faintly, but with each detail of its outline clear. After having located the hill he tried again to pick it up with the theodolite with the same poor result. This shows an increase in visibility of 30 per cent with the tinted cover-glass and had the proper filter-glass been used the result would probably have been still more favorable. Mr. Churchill does not state whether or not he used the binoculars without the tinted glass, and this fact makes the conclusion somewhat questionable in that the magnification of the binoculars is lower than that of the theodolite.

The use of color-filters is a very interesting problem and one well deserving more study and experiment. The use of proper shades of filters will increase the output of a field-party as well as improve the quality of results. Even the indication of this possibility should encourage those interested to proceed with further investigations.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT ON ABSOLUTE VALUE OF GRAVITY AT WASHINGTON

Paul R. Heyl

In addition to reporting the progress made during the past year on the determination of the absolute value of gravity at Washington, the author of this paper discussed the desirability of having absolute determinations made in other countries, as outlined in the following proposed item for the agenda of the Edinburgh meeting of the International Association of Geodesy:

"It is desirable that the absolute value of gravity be determined in as many places as possible and that adequate gravity-connections between these places be established.

"Note--The determination of the absolute value of gravity is of considerable importance to physicists but requires a long series of carefully planned experiments. The most recent determinations fail to agree with one another within desired limits, so that further study of this problem should be encouraged. Geodesists should cooperate with physicists by establishing strong connections by means of relative determinations of gravity at places where absolute determinations have been made, since without such connections the various absolute determinations are not comparable, and for the furtherance of their own science they should strengthen the gravity-net of regional and national base-stations."

National Bureau of Standards,
Washington, D. C.

RECENT DEVELOPMENTS IN GRAVITY-INSTRUMENTS

Albert J. Hoskinson

A few years ago a gravity-anomaly was something which a specialized scientist used in determining the size and shape of the Earth and in related studies, but today it has become one of the most useful tools in geophysical prospecting and in geological studies. A demand has thus been created for many additional gravity-stations throughout the world and practically every major nation on the globe is today making gravity-observations and doing research to perfect instruments that will give more accurate results and at the same time do more rapid work. The United States Coast and Geodetic Survey made a big step forward in 1932 when the new Brown instrument was put into operation. During the past year two new instruments of this type have been constructed and will be available for field-work in the near future. Considerable research has also been done to increase the accuracy of our recording devices, so that a shorter time-interval might be used in making an observation. At the present time the pendulum is swung at each new station for a period of six hours, which gives a value of gravity with an accuracy of about one part in a million.

Time-signals are now broadcast nearly every hour by the Naval Observatory which are accurate to about one-thousandth of a second. It should, therefore, be possible, in theory at least, to get the same accuracy that we now obtain in a swing of two or three hours, providing we can perfect our recording instruments so that they have an accuracy equal to or greater than the signals themselves. Our amplifier and receiving instruments have recently been re-designed and rebuilt so that we believe they have this accuracy, and test-runs now being conducted in our laboratory will soon prove whether we have achieved this goal or not. If it is desired in the future to shorten the time of observation even more, then the most logical step is to compare two pendulums directly, one swinging at the base-station and one at the field-station. This can be done by putting the beats of one pendulum on the air and recording these against the beats of the other at the field-station or more simply by recording each pendulum against some arbitrary signal, such as a time-signal. This system has been used quite extensively by some of the larger oil companies when the base-station and the field-stations were close together so that the two observers could talk directly with each other by short-wave radio telephones. I hope that we may be able to try out this system between some distant stations and our base-station at Washington during the coming year. Up to the present time we have not had the necessary instrumental equipment for such experimental work.

The growing demand for gravity-data has naturally caused the invention of many new types of gravity-instruments that will measure changes in the gravitational attraction in a shorter interval of time than required for pendulum-observations. Some of the more successful of the recent European gravimeters are: The Holweck-LeJay; the Thyssen; and the Haalck. In the United States we have the Wright instrument and one recently perfected by the Gulf Oil Company as well as many others, some of which are closely guarded secrets of the oil companies.

The Holweck-LeJay instrument is an inverted elastic pendulum which I will describe in more detail later. The Thyssen instrument is a spring instrument in which the lever-arm of the mass increases with increased gravitational attraction.

The Haalck instrument may be called a static gravimeter in which the center of mass of a floating tube changes with gravitational changes, thus causing the floater to stand at different levels. This instrument has been used quite successfully for observations both on land and sea. The Wright instrument, as you probably know, is a coil-spring instrument in which the angular deflection of a small mass is measured. The instrument of the Gulf Oil Company is also a coil-spring type.

The United States Coast and Geodetic Survey selected the Holweck-LeJay as the most promising of the spring instruments, and purchased one late in 1935. About 1000 observations in the laboratory have been made with this instrument to date. The variations are considerably larger than we had expected, but the instrument which we received was extremely sensitive to temperature-changes and also had a very poor thermometer inside the vacuum-chamber so that some of the inaccuracies are no doubt caused by this imperfection in the construction of the instrument. We hope to have this difficulty remedied in the near future and then perhaps more reliable results may be obtained. This instrument has many of the desirable features of a modern gravity-instrument. It is very portable, weighing less than ten pounds. The time of a single observation is about four minutes, and ten or fifteen such observations should give the value of gravity at any locality. If the necessary accuracy can be obtained, then it should be a very successful instrument. Some of you are no doubt quite familiar with the construction and operation of the instrument, but for the benefit of those who are not, I will describe it quite briefly. The instrument is an inverted elastic pendulum in which the mass-moment of the pendulum is opposed by the restoring moment of a small spring. The pendulum is a rod of fused quartz 4 mm in diameter and 6 cm in length. The lower end of the quartz-rod is fastened to the upper end of a small elinvar spring 0.02 mm in thickness. The lower end of the spring is fastened rigidly to the base of the vacuum-chamber which surrounds the instrument. The entire vacuum-chamber is about the size of a small radio tube.

It is obvious that the period of the pendulum and the sensitivity of the instrument to gravitational changes may be made, in theory at least, as great as desired, by making the mass-moment and the restoring moment approach equality. The manufacturers found by experiment that a period of six or seven seconds for the pendulum was the most desirable one for practical use. This produces an instrument which is so sensitive to gravity-changes that a change in the gravitational attraction of one milligal will cause a change in the period of the pendulum of 0.001 of a second. Thus if 100 oscillations of the pendulum are timed, the total time-interval need not be more accurate than one-tenth of a second. This accuracy can easily be obtained with an accurate stop-chronometer which is easily transported. The timing device furnished with the instrument may be read to hundredths of seconds, which is quite satisfactory for the work required.

The pendulum-apparatus is probably today the most dependable of the various types of gravity-instruments, but whether the apparatus of the future will be of this design, or of the spring or static types, or of some modification of either or both, or whether some entirely new design will be perfected, only time will tell and the best that we can do is to try and improve and perfect our own instruments to the best of our abilities and hold an open mind regarding all new developments until they have been very thoroughly tested and either accepted or rejected. It must also be borne in mind that the gravity-problems of all organizations engaged in this work are not exactly the same. One may be interested in small changes over a relatively small area while another may be more interested in the larger changes over an area of considerable extent. It is thus entirely possible that the instrument that is most satisfactory for one organization may not be the best for another whose aims are quite different.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE HAWAIIAN ISLAND ARC

Paul Bartsch

We have recently completed a monograph on the recent and fossil Hawaiian marine bivalve mollusks. This embraces 189 species and sub-species, which belong to 105 genera and sub-genera. Most of the fossils appear to be Pleistocene, a few may be Pliocene.

The relationship of this fauna to other faunas presents interesting problems, since the Hawaiian chain represents the most isolated oceanic islands that I know, being separated from adjacent land-areas and island groups by approximately 2000 miles.

The islands appear to rise from an even floor, not from a fault-line, but apparently through vents, through which magma has come to the land-surface, and has built up cone after cone, sometimes fusing several of them, until Mauna Kea, Hawaii, attains a height of 13,825 feet above the surface of the sea.

An examination of the soundings of the region and the regions to the north and south and east and west shows a more or less uniform depth, a little greater than 3000 fathoms. There are no north and south folds that would indicate a connection with the island-masses to the south. The affinities of the Hawaiian fauna are with the islands to the south and west. The depth that separates these regions precludes the migration of littoral forms along the bottom, and even where free-swimming larval stages are present it would be impossible for these, even if determined, to reach these islands by swimming, in the time allotted to such stages. I am therefore suggesting a reconsideration of the drift-hypothesis, by which I believe the ancestors of the Hawaiian fauna have reached these shores. I have seen clumps of trees uprooted by typhoons carried to the sea, floating upright long distances from their former station. On and among the rocks enmeshed by the roots of such trees, nestling, burrowing, and attaching mollusks may find suitable shelter and conveyance. In this instance they would have to be carried westward then northward and finally east by the Kuroshio, from whose southern edge northeast winds might, from time to time, blow them to the Hawaiian shores.

In searching the ocean-floor for north and south folds, I was struck with the large number of more or less coincident arcs forming the Pacific Isles. These arcs have a southeast to northwest trend.

I have been unable to find an explanation for this disposition, and come to you for an answer to these phenomena.

(The speaker then presented some lantern-slides showing the Hawaiian chain, the Marshall Islands, the Line Islands, the Gilbert Islands, the Ellis Group, the Louisiade Archipelago, including New Guinea, Solomon Islands, Society Islands, and the Paumotu Group, all of which show the trend referred to above.)

Smithsonian Institution,
Washington, D. C.

STUDY OF EARTH-TIDES BY GRAVITATIONAL MEASUREMENTS

R. D. Wyckoff

Introduction

The existence of earth-tides has been shown by (1) studies of long-period ocean-tides and (2) the tilt of land-surfaces usually measured by horizontal pendulums, and (3) by observations on the variation of gravity at a given place. The method involving the study of ocean-tides may be dismissed as having only historical interest since any significant measurement of earth-tides by this method is quite impracticable. The second method has been used extensively since horizontal pendulums or equivalent devices of adequate sensitivity for measuring the tilt of land-surfaces have long been available. However, though the required measurements may be made, the problem of interpretation in terms of vertical displacement necessarily involves the integration of many simultaneous observations covering a large area, for normal variations in the effective rigidity of the Earth's crust due to variations in lithology or structural features result in spurious local deformations which must be eliminated from the broad-scale picture if a true measure of the vertical tidal displacement is to be obtained. Clearly, observations at an excessively large number of stations would be required and the final interpretation would present an enormous problem. Indeed, the difficulties appear quite insurmountable if one is to judge from results thus far obtained and the reports of recent work (Travaux de la Association de Géodésie, Union Géodésique et Géophysique Internationale, Rapport sur les Marées de l'Écorce Terrestre, Paris, 1933).

Evidently the most direct and desirable approach to the problem is that involving the measurement of variations in gravity at a given place. While an attempt to do this was reported as early as 1914 by Schweydar (Beobachtungen der Änderung der Intensität der Schwerkraft durch den Mond, SitzBer. Königlich-Preussischen Akademie der Wissenschaften, p. 454, 1914), the instrumental problems involved have deterred progress until the recent work of Tomaschek and Schaffernicht (Untersuchungen über die zeitlichen Änderung der Schwerkraft, Annalen der Physik, v. 15, p. 787, 1932) showed clearly the practicability of the method.

The purpose of the present report is further to emphasize the feasibility of gravitational measurements in the study of earth-tides with the hope that some of the effort heretofore expended on other methods may be attracted to this more promising field. However, attention is called to the fact that the material to be presented here does not represent the results of an effort especially directed to earth-tide studies. Rather, the work is a by-product incident to the development of a portable gravimeter for an entirely different purpose. The instrument was purely an experimental one and the records were made to study the performance of spring-materials. Nevertheless, while neither the instrument nor its mode of operation was particularly adapted to tidal observations, the results are indicative of promising rewards if a concerted effort is made to attack the problem by this method.

Instrumental requirements and design

The maximum amplitude of the tide-producing force is approximately 2×10^{-7} g, or a total variation (minimum to maximum of the curve) of 4×10^{-7} g, the exact value depending upon the latitude of the observing station. Thus, to obtain significant results, the measuring instrument must have a sensitivity of at least 10^{-8}g and preferably 10^{-9}g. Moreover, it must be a recording type so that continuous records can be obtained over long periods of time.

Tomaschek and Schaffernicht are using an improved instrument of the type described by A. Schmidt (Beitr. Geophysik, v. 4, p. 109, 1900), consisting of a weight suspended from a spiral spring coupled with a twisted bifilar suspension carrying a small part of the load. The torque developed by the bifilar suspension is balanced by an opposing torsion in the spring. Such a system may be adjusted to operate very close to its position of unstable equilibrium and in this condition, if carefully designed and provided with a stable spring, very small changes in weight produce considerable angular rotations of the suspended system. As would be anticipated, the actual attainment of the requisite sensitivity together with adequate stability is by no means a simple problem.

A very cursory consideration of the sensitivity-requirements suffices to show the expedient trend in the design of a suitable instrument. The simplest device would consist of a weight suspended freely from a suitable spring. Assuming the spring to have a displacement of one meter under the applied weight, then a change of 10^{-8}g would produce a deflection of 10^{-6}cm, or about 1/50 of a wave-length of the sodium-D line.

Thus, even the minimum permissible sensitivity would be out of the range of any direct-reading interferometric device, and attainment of the desired sensitivity ten times this value quite impossible, particularly if the continuous recording problem is considered. Moreover, it is evident that a very high order of mechanical amplification would be required between the moving weight and the recorder regardless of the type of optical device introduced. In the elimination of this excessive amplification-requirement resides the particular attractiveness of the general type of design wherein advantage may be taken of an operating equilibrium-position close to the point of instability. This class of instrument provides high sensitivity in the moving system itself with the required optical or mechanical amplification correspondingly reduced.

The instrument used in the work to be described comprised essentially a modified Galitzin vertical seismograph. (The use of this type of instrument was suggested by V. V. Vacquier, Gulf Research and Development Corporation.) With this device adjusted close to the critical point and provided with moderate optical amplification, ample sensitivity may be obtained. Using a spring whose actual displacement was about 25 cm, corresponding to a normal oscillating period of about one second, the instrument could easily be adjusted for a 15-second period and on occasions to one of over 20 seconds. Since the sensitivity of the device to gravitational changes is proportional to the square of the period, an amplification of at least 400 was obtainable in the moving system itself, as compared with a simple spring-suspended mass of the same spring-displacement. Thus such operation was equivalent to the use of a simple spring having 10,000-cm displacement.

A reasonable optical amplification comprising six reflections from a mirror mounted on the axis of the moving arm and an optical path of about 150 cm, permitted direct photographic registration on a tape moving about 2.5 cm per hour. The tape was driven by a synchronous motor operating from the usual clock-controlled power-supply, but in addition, for convenience and certainty in timing, hourly time-breaks were recorded on the tape by means of an auxiliary clock.

The design of the gravimeter is shown schematically in Figure 1. The spring used was constructed of special material having a low rate of creep and temperature-coefficient. In addition, the instrument was very carefully thermostated so that no short-period temperature changes as great as 0°.001 C could be detected. Being purely an experimental model, the instrument was not sealed in an airtight container so that spurious deflections due to barometric-pressure changes (buoyancy-effects) required attention. Compensation was provided by a "counter-volume" of magnesium. Examination of records taken during periods of pronounced barometric-pressure changes showed no correlation between pressure and instrument-deflection so it was assumed that the buoyancy-compensation was satisfactory. The sensitivity of the instrument to tilt was minimized by an auxiliary verticality-adjustment of the spring-support. With the exception that the beam-system was supported on a knife-edge, and with the additional details described above, it will be clear that the well-known theory of the Galitzin seismograph applies and further instrumental discussion is not warranted.

The tide-producing forces

Table 1 tabulates the six components used in computing the theoretical tide-producing force. These are by no means the total number but include those short-period components having the greatest amplitudes; the remainder would probably contribute only a few per cent additional. The amplitudes given are for Pittsburgh, Pennsylvania (40° 26' north latitude), where the experimental observations were made. It will be noted that the maximum possible variation in g (minimum to maximum of curves) due to the tidal force alone is about 3.4 × 10^{-7}g.

It should be mentioned that a fortnightly component having quite appreciable amplitude has not been included in the calculations because of the impossibility of resolving the instrumental records for such long-period fluctuations. Variable drift present in the experimental instrument precluded such analysis and at times even gave some trouble in the diurnal components. In fact, it is questionable whether any instrument can be constructed which will permit an accurate analysis of its records for very long-period tides.

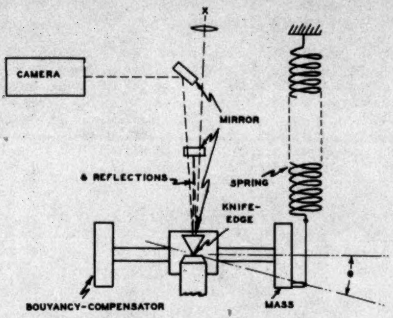

FIG. 1—SCHEMATIC DIAGRAM OF GRAVIMETER USING THE PRINCIPLE OF THE GALITZIN VECTICAL SEISMOGRAPH

Table 1--Tabulation of principal short-period components of tidal forces at Pittsburgh, Pennsylvania, latitude (φ) 40° 26' north, longitude 80° west ($\cos^2 \varphi = 0.579$, $\sin 2\varphi = 0.987$)

Tide	Description	Period in hours	Amplitude and phase
M_2	Principal lunar Semidiurnal	12.4206	7.60×10^{-8} g f $\cos^2 \varphi \cos (V+u)$ Ampl. = 4.34×10^{-8} g
S_2	Principal solar Semidiurnal	12.0000	3.55×10^{-8} g f $\cos^2 \varphi \cos (V+u)$ Ampl. = 2.06×10^{-8} g
N_2	Larger lunar elliptic Semidiurnal	12.6584	1.48×10^{-8} g f $\cos^2 \varphi \cos (V+u)$ Ampl. = 0.84×10^{-8} g
K_1	Lunisolar diurnal	23.9345	4.45×10^{-8} g f $\sin 2\varphi \cos (V+u)$ Ampl. = 4.64×10^{-8} g
O_1	Principal lunar	25.8194	3.17×10^{-8} g f $\sin 2\varphi \cos (V+u)$ Ampl. = 3.41×10^{-8} g
P_1	Principal solar Diurnal	24.0659	1.48×10^{-8} g f $\sin 2\varphi \cos (V+u)$ Ampl. = 1.46×10^{-8} g

Maximum total amplitude at Pittsburgh = 16.75×10^{-8} g

f = coefficient varying independently for individual components in accordance with long-period astronomical variations.

(V+u) = function of longitude and astronomical data giving exact longitude of Sun and Moon at any particular time.

Experimental results

The most convenient method of representing and studying tidal observations involves the reduction of the continuous records into "harmonic" components following the methods commonly applied to tidal records. Obviously only data which are quite continuous over long intervals of time and strictly quantitative may be subjected to such analysis. Unfortunately, in the present case the data are not suitable for this treatment since, as already mentioned, the original aim of the work did not include the tidal problem, whereas it is quite evident that any deliberate effort so directed involves specialized problems in instrument-design and operation.

The most serious deficiency was the lack of an accurate calibration of the instrument so

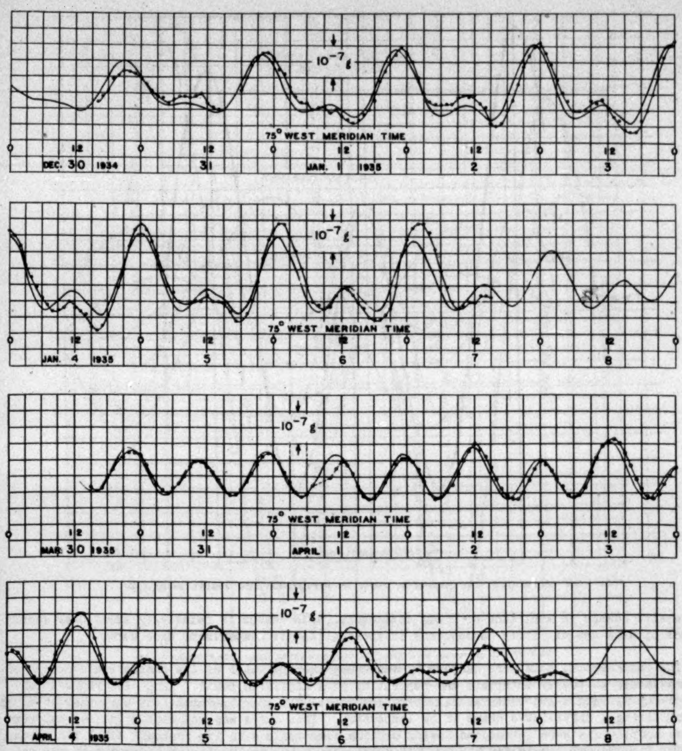

FIG. 2—TYPICAL COMPARISON OF CALCULATED TIDAL FORCE AND OBSERVED GRAVITATIONAL VARIATIONS (PLOTTED CIRCLES ARE OBSERVED CURVE-ORDINATES ON ARBITRARY SCALE)

that the records could not be reduced to accurate gravity-values. Moreover, a single calibration would be inadequate since instruments of the general instability class are inherently non-linear, their characteristic being a sensitivity which is a function of the proximity of the equilibrium-position to the critical instability point. Thus the normal drift of the equilibrium-position, caused by creep of the spring, resulted in a continuously changing and unknown calibration. For this reason particularly, the usual harmonic analysis could not be applied. Alternatively, a more pictorial presentation has been used, which, while much less satisfactory technically, does permit qualitative correlation that is adequate for present purposes and involves only a comparison of the calculated and observed gravitational variations plotted as continuous curves.

The tide-producing force was calculated as the summation of the six components tabulated in Table 1 and plotted as a continuous curve representing the period from December 1, 1934 to April 9, 1935. This was accomplished quite easily by constructing a large-scale template for each of the six components, each template covering about 36 hours on the time-scale. The individual component-curves were then drawn superposed and the ordinates added at hourly intervals. In order to prevent any error due to progressive phase-shift in using the templates, a direct calculation was made at intervals of about four days and by adjustment to fit these points any accumulative error on the time-axis was eliminated. While this process does not take into account a

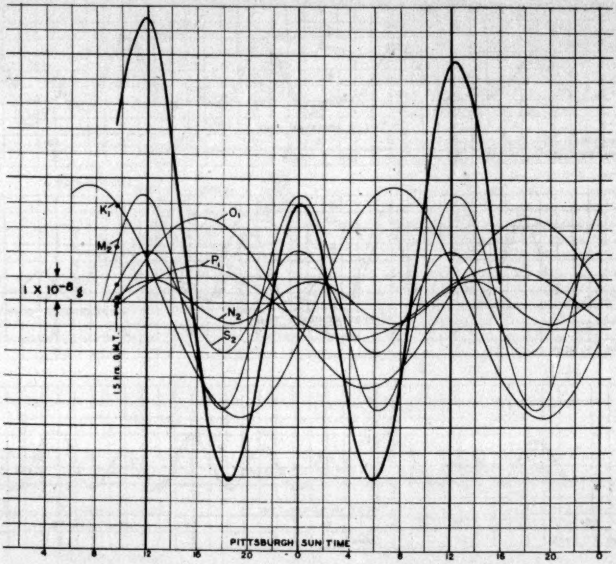

FIG. 3—THE CALCULATED TIDE-PRODUCING FORCE AT PITTSBURGH FOR AUGUST 24-25, 1934

progressive change in amplitude of lunar components, this change is relatively small over short periods of time and of little consequence in the qualitative comparisons made here.

The instrumental data were handled by measuring the ordinates of the photographic record of the gravimeter at hourly intervals and replotting on a magnified scale. This plot represented the gravity-variation and instrumental drift combined. The gravity-variations were then obtained by subtracting a drift-curve drawn in by inspection. This curve was not linear but was so drawn that no corrections were introduced having periods comparable with the residual tidal variations. In fact, the control-points for the assumed curve were taken as the lowest ordinates of the recorded curve and a smooth curve was drawn through them. While this procedure appears quite arbitrary, there was no alternative and it should be emphasized that any deliberate forcing of the drift-curve was conscientiously avoided. However, in the finally assembled data the observed gravity-results were plotted using an arbitrary instrument-calibration, the value of which was changed only when readjustment of the instrument was made. In this manner the observed and calculated curves were given approximately equal amplitudes so as to facilitate qualitative correlation. Since the sensitivity of the instrument is known to change progressively with the drift of its equilibrium-position and no compensating change in instrumental constant was made, the change in comparative amplitudes evident in the curves is explained.

Figure 2 shows representative portions of the final plots. The interval from December 30, 1934 to January 7, 1935, shows a period during which the diurnal components predominate, while the records of March 30 to April 7, 1935, cover a period of pronounced semidiurnal variations. The smooth curve is calculated, while the circles show the observed variations read at hourly intervals. These curves are intended to serve no purpose other than to show the definite correlation between the theoretical tide-producing force and the observed gravitational variations. However, the relative phase of the observed and calculated curves should be significant since the instrument-calibration is not involved. In this connection, it should be mentioned that the average lag of the experimental behind the theoretical curves, obtained by consideration of all data, is about 50 minutes in time or approximately 12°5 angular lag. It is not known whether the small lags evident in some of the semidiurnal variations of Figure 2 should be considered as

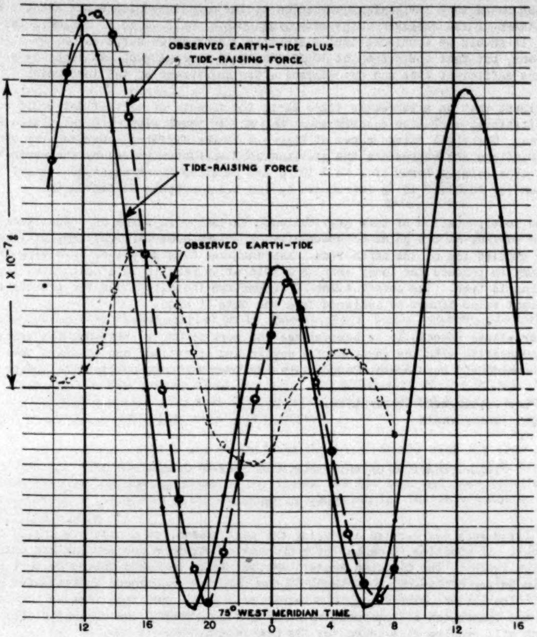

FIG. 4—CALCULATED AND OBSERVED GRAVITY AND THE DERIVED EARTH-TIDE COMPONENT FOR AUGUST 24-25, 1934

significant since the lower accuracy of the observations at the smaller amplitudes may have introduced the apparent shift.

Further, to illustrate the effectiveness of gravitational studies, the data from a single 24-hour record of excellent quality will be considered quantitatively. Quite fortuitously the instrument-adjustment gave periods of 21.8 and 21.5 seconds, respectively, at the beginning and end of the record with a correspondingly high sensitivity. These periods were used in assigning an approximate value for the sensitivity, for in a simple spring-suspended mass-system the period gives directly the total spring-displacement and the effective sensitivity under equilibrium-conditions. In the present case (Fig. 1) it is evident that under dynamic conditions the period is lengthened by the moment of inertia of the moving system about its axis of rotation without a corresponding increase in sensitivity of the device as a deflection-instrument. However, assuming the sensitivity as proportional to the square of the observed period and ignoring the spurious contribution to the period by the angular moment of the moving system, the derived sensitivity will be too high. Thus the measured gravity-variations will be smaller than the actual. This fact should be kept in mind in considering the data which follow, for, lacking a more satisfactory method, the instrument-calibration was determined in the above manner to be 2.1×10^{-7}g per cm deflection on the photographic record.

Figure 3, which shows the calculated tidal force plotted against Pittsburgh sun time for the period concerned, August 24-25, 1934, is of interest in showing the relative amplitudes of the six components considered. Obviously, increasing ordinate represents increasing vertical force directed away from the earth or decreasing resultant gravity. Figure 4 shows the calculated tide-producing force and the observed gravitational variation plotted against Eastern Standard Time.

It will be noted that the maximum variation of the calculated force was about $1.85 \times 10^{-7}g$ and the smoothness of the observed curve recording such a small value of Δg indicates excellent performance. It should be mentioned that a strictly linear drift-curve was assumed in reducing the observations, but that the points at 10:00 and 11:00 a.m., August 24, might be slightly erroneous because sufficient time had not elapsed after adjustment of the instrument.

It is evident that on a perfectly rigid Earth the absence of earth-tides would result in an observed gravitational variation exactly equal to, and in phase with, the calculated tide-producing force. The light dotted curve of Figure 4 is the difference between the observed and calculated variations and represents the gravitational variation caused by the earth-tide itself. Thus a tide-raising force of $1.85 \times 10^{-7}g$ has resulted in an extraneous gravitational variation amounting to $0.7 \times 10^{-7}g$ introduced by the tidal warping of the Earth.

While the interpretation of this gravitational variation in terms of actual tidal elevation of the Earth's surface at the point of observation involves some difficulties, of immediate interest is the implied lag of the earth-tide. Astronomical considerations involving the energy-losses necessary to produce the lunar secular acceleration results in a calculated lag of about $1^{\circ}\!.5$ or 6 minutes in time. The observations at Pittsburgh indicate a lag far greater than this although an exact value cannot be assigned from the data at hand.

The writer wishes especially to acknowledge the work of Dr. A. Hoyt and his assistant, A. Carnvale, in connection with the instrumental design and operation, and to thank the Directors of the Gulf Research and Development Corporation for permission to publish this paper.

Gulf Research and Development Corporation,
Pittsburgh, Pennsylvania

FIELD-OPERATIONS OF THE GEODETIC SURVEY OF CANADA FOR 1935

Noel J. Ogilvie

Geodetic field-work was carried on during the past season, on a moderate scale, in five different provinces. In addition, a number of astronomical stations for mapping and charting purposes were established in the Canadian Eastern Arctic; while in Newfoundland several engineers of the Geodetic Survey of Canada, Department of the Interior, commenced an extensive scheme of triangulation. The latter undertaking, the result of a joint agreement between the Government of Canada and the Commission of Government of Newfoundland, marked the beginning of a field-operation which will require five years for its completion.

In general, the activities of the 1935 season were considerably more extensive than those of the two preceding years. While the field-methods used in carrying on the various phases of the work were similar to those generally adopted in modern practice, a special interest centered around the observation of the horizontal angles of the triangulation-nets. The 5 1/2-inch lightweight theodolites, which had recently been remodeled at Ottawa, were subjected to their first critical test under actual field-conditions.

Precise levelling

Precise levelling was carried on in Ontario and Manitoba, two parties being engaged in the former province and one in the latter.

By working along the Canadian National Railway lines on the east and west sides of Lake Manitoba adequate levelling-control was provided for this section of Manitoba. The level-lines were run from Winnipeg to Steep Rock and Gypsumville and from Portage la Prairie to Alonsa. A 30-mile branch line of levels was run across country from Mulvihill on the Winnipeg-Gypsumville line to Siglunes on the east coast of Lake Manitoba. A 15-mile extension was also run from Alonsa on the west side of the lake to Kinosota directly opposite Siglunes.

In the month of December, after the formation of the ice, the Manitoba Department of Mines and Natural Resources made a precise-level connection across the narrows of the lake between Kinosota and Siglunes, a distance of 5 1/2 miles. In this way, a 266-mile circuit of precise levelling was completed with a closure of 0.35 foot.

In Ontario, precise-levelling operations were carried out in the area which lies northeast of Lake Superior and east of Lake Nipigon. Here also, the lines of the Canadian National Railway were found to be the most suitable routes along which to project the levelling lines. Several large circuits already in existence in this area were broken up into several smaller loops.

The following is a summary of the precise levelling carried on in 1935:

Lines of levelling	Miles
Winnipeg to Steep Rock and Gypsumville	167.0
Mulvihill to Siglunes	29.7
Portage la Prairie to Kinosota	87.7
Nipigon to Nakina	161.4
Longlac to Tionaga	273.9
Total	719.7

Of the 720 miles levelled, 672 were along lines of the Canadian National Railway and 48 along country roads.

Geodetic astronomy

Astronomical field-work was carried on in Ontario, Nova Scotia, Quebec, the Canadian Eastern Arctic, and in Newfoundland.

In connection with water-power developments in northern Ontario, a scheme of secondary triangulation was projected last summer along Lac Seul, 125 miles east of the Ontario-Manitoba Boundary. Due to the remoteness of this area from existing nets of triangulation, it was necessary to establish it, for the time being, on a local datum.

A precise astronomical station was established for this purpose near the town of Hudson. Observations for latitude, longitude, and azimuth were made at this point. When the main Ontario triangulation-scheme is ultimately extended to include the Lac Seul net, the local astronomical station will serve as a Laplacian point and also as a station for the determination of the deflection of the vertical.

In Nova Scotia, an astronomical party was engaged on isostasy field-work. Deflections of the vertical were determined at ten additional points. In all, the deviation of the plumb line has been determined at 65 points in the maritime provinces and lower Quebec. Preliminary investigations of the geoid for that part of Canada have been commenced but until more data have been determined it has been considered impracticable to proceed with a complete least-square adjustment to find the various unknowns.

During the past season, an officer of the Geodetic Survey of Canada accompanied the "Eastern Arctic Patrol" which visits each year some 20 trading-posts and police-stations scattered along the coasts of Hudson Bay, Hudson Strait, and the western coast-line of Davis Strait and Baffin Bay. Observations for position were made on this itinerary as far north as Craig Harbour on Ellesmere Island in latitude 76° 12'.

While this trip was chiefly of the nature of a reconnaissance, astronomical equipment was taken along and observations for latitude and longitude were secured at eleven of the points visited. On this work, where the stay at each port of call was short, it was not considered feasible to use an astronomical telescope adjusted in the meridian. Instead, a 5 1/2-inch lightweight theodolite was used. With the telescope clamped at a fixed angle of 60°, a number of stars were observed in each quadrant in a manner similar to observation with the prismatic astrolabe. No particular difficulty was experienced in securing good fixations by this method.

While it is true that the determination of time becomes increasingly difficult as one approaches the pole, yet it must be recognized that the lineal equivalent of a second of arc of longitude measured along the prime vertical is only about 24 feet in latitude 76° 12' compared with 72 feet in latitude 45°. For this reason, the permissible error in the determination of time may be three times as great in latitude 76° as in latitude 45° without increasing the relative errors of the position-determinations.

In spite of limited observations, most of the position-determinations indicate an accuracy of about 100 feet. Many stations of this nature could be advantageously established in the north for use in mapping and charting in sections where it is not feasible at present to extend triangulation-nets.

Triangulation

Triangulation field-work was carried on at Lac Seul in Ontario, at Fort William on Lake Superior, and in British Columbia.

The Lac Seul net of second-order triangulation covers a small area about 125 miles east of the Ontario-Manitoba Boundary and to the north of the Canadian National Railway. Lac Seul impounds water for power-plants serving mining areas and also acts as a storage-reservoir for power-plants on the Winnipeg River. Various surveys had already been made or were proposed to be made in this area. A network of geodetic triangulation was desired to serve as a basis of coordination for these surveys, and also to provide a control for further detail-surveys.

In the Lac Seul area, particularly on the north side of the Lake, there are few isolated hills. The ridges are heavily wooded and are approximately the same height. This necessitated the use of short lines from five to fifteen miles in length. The net which had an axial length of 60 miles covered 450 square miles. It commenced at the railway track at Hudson, along which the base-line was located. From there, it extended northward and westward following the main part of the Lake.

Daylight signals were used throughout. Towers which averaged 41 feet in height were built at all main stations. Diamond-shaped, cotton-covered targets were used to mark the stations. The observations of the horizontal and vertical angles were made during the late afternoon when conditions were most favorable.

The average triangular closure was 0.93 second; the maximum closure was 2.50 seconds. The side-equations of the component figures of the net all showed a high order of accuracy. Judging by these criteria, the net might almost be considered comparable in accuracy with primary work.

A primary triangulation-party was engaged in British Columbia on reconnaissance and the measurement of horizontal angles. The work of angular measurement was carried on in the area adjoining the main line of the Canadian Pacific Railway from North Bend, 125 miles northeast of Vancouver, through Ashcroft, Kamloops, and Salmon Arm to Sicamous, a distance of 125 miles.

Fourteen primary stations were occupied in connection with this work. Twelve supplementary stations were also located by intersection. The area covered was about 6,400 square miles. The primary stations were, for the most part, located on the summits of mountains ranging from 5000 to 8000 feet in height. Deep snow on the mountains retarded the progress of the work during the first part of the season. On some of the slopes 15 or 20 feet of snow was encountered. One of our light-keeping parties reported loose snow almost waist deep in places on the slope of Mobley Mountain.

The British Columbia party started work on May 7 at the Salmon Arm base-net. This base had been located and measured in 1912 by the Topographical and Air Survey Bureau, Department of the Interior, in connection with the triangulation of the Railway Belt in British Columbia. Some work was also done this year in re-clearing the base-line and preparing it for remeasurement with geodetic accuracy.

In addition to this work, there was the completion of the reconnaissance along the Cariboo highway, where a small gap between Ashcroft and Quesnel was filled in. Five primary and a number of secondary stations, constituting about 70 miles of axial length of net, were located in this area.

At Fort William, Ontario, the harbor-area instead of fronting only on Lake Superior, extends a distance of four or five miles up the Kaministikwia River and its branches. In order to fix permanently the 25 miles of harbor-line, the line between the harbor-area and the private properties fronting upon it, the Geodetic Survey of Canada, at the instigation of the Public Works Department, commenced a triangulation-system of the area involved.

A primary and two secondary triangulation-stations were already in existence near Fort William. From these points, a triangulation-net comprising 32 stations was expanded. Three stations of the net were located on the concrete roofs of large grain-elevators in that area.

Two distinct types of daylight signals were used. So appropriate were they in design that they contributed materially to the marked accuracy of the angular measurements. On short lines, a bricklayer's plumb 3 inches wide with a 1/4-inch white strip painted down the center line was used. The foot of the signal was, of course, provided with a projecting iron pin, which was placed in the small hole marking the center of the triangulation-tablet. The bracing, by means of small multi-strand wire cables and turn-buckles, proved eminently satisfactory.

The other signal, for longer lines, comprised an eight-foot upright, 3 inches by 3 inches, painted black and white in alternate strips. Near the top, two galvanized iron vanes two feet square were inserted in slots at right-angles to each other. The vanes served as finders or identifiers. The actual pointings were made on the uprights. The facility with which signals of this type could be sighted upon from any other station proved to be a great advantage. When once plumbed in position over a station, the multi-strand wire cable braces, suitably tightened with turn-buckles, retained the signals in position indefinitely.

The average triangular closure of 40 triangles of this net was 1.15 seconds. The mean of the corrections to the directions, derived from the adjustment, was 0.38 second. The measurement of the horizontal angles was of course carried on during the most favorable periods of the day--early morning or late afternoon and evening.

In connection with this net, it is proposed to calculate the position of each geodetic station by a system of plane coordinates referred to some suitable origin. Before the work is completed, a base-line will be incorporated into the scheme and a Laplace station probably included to strengthen and check the accuracy of the net.

Field-performance of remodelled light-weight theodolite

During the past season, a number of remodelled 5 1/2-inch light-weight instruments were used for the occupation of 61 primary and secondary geodetic stations. The engineers who used these instruments in the field all report satisfactory performance, their ability to close the horizon satisfactorily, and a high order of accuracy in triangular closures. It is realized, however, that the crucial test of the instrumental performance and the skill of the observers will be more truly made manifest when the nets involved are subjected to the added tests of base-lines, Laplace points, and loop-closures.

In general, the results of observations made during 1935 appear to be highly satisfactory. After the remodelled instruments have been subjected to several years' field-usage, the effects of abrasion and wear on the remodelled bearing surfaces may be more satisfactorily studied.

Geodetic operations in Newfoundland

Canada's primary nets of triangulation in the Maritime Provinces and in Lower Quebec form a partial loop almost encircling the Gulf of St. Lawrence. Some years ago two primary triangulation-stations were established by the Geodetic Survey of Canada at the southwest extremity of Newfoundland by projecting a quadrilateral across Cabot Strait from the north end of Cape Breton Island.

The Commission of Government of Newfoundland, in carrying out a policy to advance the development of the country's natural resources, became aware of the unsatisfactory nature of their existing maps and the lack of any system of control-survey. It was realized that a geodetic survey of the country was desirable. At the same time it was realized that Canada's scheme of triangulation would be greatly strengthened by the completion of the gap between the south end of Newfoundland and the Strait of Belle Isle, as the mathematical advantages of a loop-closure would be obtained. Moreover, the future demarcation of the Inter-Dominion Boundary between Canada and Labrador would have the advantages of a mathematically adjusted loop of primary triangulation extending through the area adjacent to the southerly part of the boundary-line.

By an agreement between the Government of Canada and the Commission of Government of Newfoundland, the Geodetic Survey of Canada is to provide the technical personnel, loan the instrumental equipment, and compute and publish the resulting data. Newfoundland is to bear the entire cost of the field-work estimated to be $75,000.

During the past season, two engineers of the Geodetic Survey of Canada carried out the reconnaissance for the proposed triangulation. Aeroplanes were used for the preliminary investigations. The triangulation-stations selected from the air are to be "ground-checked" to ensure intervisibility of stations before the work of observation is commenced.

A main net of primary triangulation, extending from Cape Ray at the south to the Strait of Belle Isle at the north, has been found to be feasible. A secondary net, branching off from the main net, near the northerly end, has been extended eastward to the city of St. John's. Further extensions of the scheme will, no doubt, be made later by the Newfoundland officials.

Altogether, 107 triangulation-stations were located involving axial lengths of nets totaling 650 miles. Some of the ground-checking of the reconnaissance has already been done and 23 stations have been marked on the ground and prepared for observation.

A base-line near St. Fintans has been located and partially prepared for measurement. Its total length will be in the neighborhood of six miles.

During last year's field-season, the Newfoundland authorities carried on a small amount of topographical mapping. To supply local datums in connection with this work, the Geodetic Survey of Canada established precise astronomical stations at Sops Arm on the northeast coast and St. Lawrence on the south coast. These observations indicated that the shore-line at Sops Arm is shown 1 1/2 miles out of position on the maps of Newfoundland. The shore-line at St. Lawrence was found to be 1/2 mile in error on the local maps.

Observations for astronomical position were also made on the site of a historic, old admiralty astronomical station located at Fort Townsend in St. John's. This station was marked by a block of sandstone about 18 inches square with its top level with the ground. Upon its upper face was marked "1828", the date of observation, together with its observed position in longitude east of Halifax and west of Greenwich. It also showed the observed latitude and the magnetic deviation at that time.

The comparison between the values secured 107 years ago, with less precise instruments and methods, and the values determined in 1935 by modern technique may be of interest. The longitude was, no doubt, determined in 1828 by the transportation of chronometers. The comparison is as follows:

Year	Latitude	Longitude west of Greenwich
	° ' "	° ' "
1828	47 33 42	52 45 29
1935	47 33 55.78	52 42 46.1
Difference	13.78	2 42.9
Difference in feet	1,396	11,175

As might be expected, the discrepancy in longitude is much greater than that in latitude.

The value of the magnetic variation inscribed on the sandstone tablet in 1828 was "28° 47' westerly".

During the field-season of 1936 the observation of horizontal directions will be commenced and continued throughout the season by two observing parties. It is not anticipated that progress on this work will be extremely rapid. The dearth of roads and railways adds considerable difficulty to the problems of transportation in carrying on geodetic operations in Newfoundland.

Geodetic Survey of Canada,
Department of the Interior,
Ottawa, Canada

PROGRESS OF THE GEODETIC WORK OF THE COAST AND GEODETIC SURVEY DURING THE PAST YEAR

C. L. Garner

The geodetic program of the United States Coast and Geodetic Survey, at first augmented by the increase of our regular appropriation in the year 1931 and later further increased by allotments of emergency funds, was very drastically curtailed in July, 1935, due to the exhaustion of both emergency and regular appropriations. Since that time it has been possible to continue only such field-work as was required to smooth out some of the ragged ends, to obtain base-measurements and astronomic observations as necessary for the adjustment of the various loops of triangulation, and to continue gravity-work in accordance with our plan of cooperation with a number of scientists who were sponsoring this type of work.

From April until July, inclusive, 1935, approximately 1300 people were employed in the field in the extension of control-work and associated activities by this Bureau. In addition to these, a large force of computers, including more than 150 who were paid from emergency funds and the regular force of approximately 50 employees in the Washington Office, were engaged in the

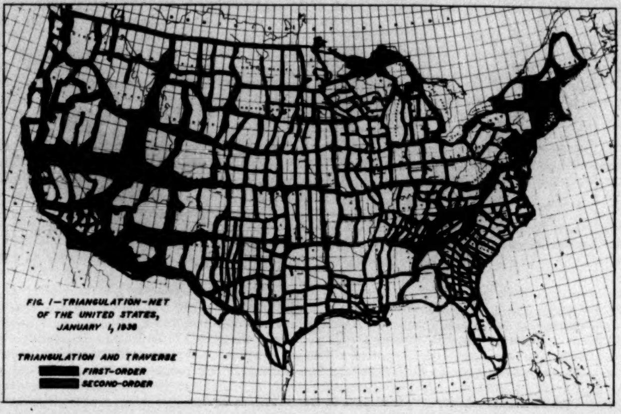
FIG. 1—TRIANGULATION-NET OF THE UNITED STATES, JANUARY 1, 1936

various steps required in compilation at the office leading to the publication of the results. Due to the fact that emergency funds for both field and office were exhausted at approximately the same time, it has naturally been impossible to put any appreciable amount of the field-records received during the last year of the period of accelerated work in any form approaching the stage of publication. In fact, such data will have to remain in the files of the Bureau unavailable for issue until such time as the necessary personnel may be obtained with which to make the required reductions. Our regular office force is so small that it can hardly scratch the surface aside from the routine duties required in furnishing information and carrying on certain well-established office procedure. Approximately $1,000,000 was spent during the year.

The work in the field and office accomplished since April 1, 1935, is as follows: Triangulation--first-order 3,605 miles, second-order 2,213 miles, total 5,818 miles; leveling--first-order 3,446 miles, second-order 32,399 miles, total 35,845 miles; first-order bases, 12 with a length of 69 miles; astronomic observations at Laplace stations, 91 (include 91 longitudes, 67 latitudes, and 90 azimuths); total first- and second-order triangulation completed in United States to March 31, 1936, 66,958 miles; total first- and second-order leveling completed in United States to March 31, 1936, 261,366 miles.

Publications received or in the hands of the printer during the year are as follows:

Special publications--
192 - First- and second-order triangulation and traverse in North Carolina (1927 datum)
194 - Manual of traverse computation on the Lambert Grid
195 - Manual of traverse computation on the transverse Mercator Grid
5 (Revised edition) - Tables for a polyconic projection of maps and lengths of terrestrial arcs of meridian and parallels based upon Clark's reference spheroid of 1866
198 - First- and second-order triangulation in Tennessee (1927 datum)
199 - Tables for determining the form of the geoid and its indirect effect on gravity
200 - Formulas and tables for the computation of geodetic positions on the international ellipsoid
202 - First- and second-order triangulation in California
203 - First- and second-order triangulation and traverse in Minnesota
204 - A determination of the relative values of gravity at Potsdam and Washington

Serial publications--
583 - Control-surveys and their uses
584 - Azimuths from plane coordinates

These publications naturally include field-work done prior to the period covered by this report, as considerable time is required in the total processing of the material and putting it

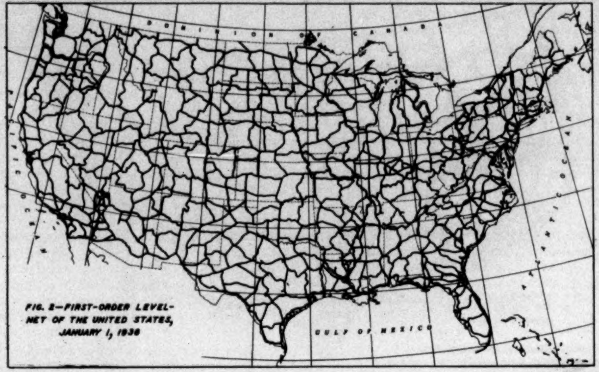

FIG. 2—FIRST-ORDER LEVEL-NET OF THE UNITED STATES, JANUARY 1, 1936

in form for publication. Several other publications are now ready for the printer as soon as the necessary funds are available for printing.

Objective

In the extension of its control-work the United States Coast and Geodetic Survey has as its aim the furnishing of such horizontal and vertical control-data as will best meet the needs and be of the greatest service to the public in so far as funds are made available for carrying on the work. The Survey is ever searching out and seeking ways and means by which the service can be made more adaptable and brought nearer home to the average citizen.

In order to accomplish this main objective, certain fundamental principles have to be constantly borne in mind by those responsible for the work, both in the field and office, and it seems well that some of these be recalled in brief outline.

(1) The stations and bench-marks of both the horizontal and vertical control-nets shall be so distributed as to best serve the surveying and engineering public without losing sight of the fact that it is impossible to cover the country with control in any short period of time and, therefore, the distribution of it must in any event be a compromise between that which is desired and that which is possible to obtain, or in other words, a compromise between the ideal and the practical.

(2) In the extension of these nets over the country, ties must be made to existing control of other organizations so that full benefit may be had in the future of all past surveys which have been planned and executed on a basis to be of value after completion.

(3) The schemes must be so laid out that connection may be easily obtained in the extension of additional control after the fundamental federal control-net has been completed.

(4) Triangulation-stations, where practicable, must be placed close to highways or public roads for purposes of accessibility and ease in making ties.

(5) Azimuth-marks must be placed at all triangulation-stations in order that engineers may be furnished with a position and an azimuth at each station.

(6) The location of stations and bench-marks must be such that a minimum of them will be destroyed or disturbed by future construction, road-building, etc.

(7) Stations must be established within the area of or close to all cities and towns of any appreciable size, in order that local engineering or city-control work may be tied into the federal fundamental net when and as desirable. Similar stations should be established on the grounds of educational institutions, particularly those giving courses in engineering, in order

that engineering students may become more awake to the importance of this class of work and the bearing it has on property boundaries and titles thereto.

In carrying on this work, contact with the public, particularly owners of property, must be tactful and educational, to the end that they may understand the value of such stations and bench-marks and know that it is to their interests to preserve them. Citizens generally should be encouraged to report on the condition of stations and bench-marks and to assist in the preservation of them where possible.

In the extension of arcs of triangulation (in so far as funds are available) stations must be established sufficiently close that the minimal control-requirements for aerial photographing and the reduction of planimetric maps may be met without having to go into the same area at a later date to extend additional horizontal control-work.

Bench-marks are established at intervals of approximately one mile in open terrain and at a much closer average spacing in cities, in order that elevations may be available without the necessity of an engineer going too far for the desired connection.

It is generally recognized among engineers and surveyors that the present system of extending nearly all surveying and engineering projects on local datums, without any means of interreference from one to another even when they are almost in physical contact on the ground, causes a great amount of confusion and wasted effort, and is therefore entirely wrong and should be corrected by the adoption of some standard, uniform system. Generally speaking, spherical coordinates have not been adopted for reference on local engineering projects principally because they are not particularly suited to small detailed surveys and because they require much more work in making the computations than do plane coordinates. Definite progress in correcting these conditions has been made within the last two years in adopting a form of procedure whereby it is believed horizontal control-data may be made of much greater value generally. Reference is made to the systems of plane coordinates which have been developed by the United States Coast and Geodetic Survey for all of the states.

These coordinates have been devised with the idea that they are adaptable to the practical use of every engineer and surveyor irrespective of the degree of accuracy of his work. In the case of surveys involving an accuracy of not more than one part in 10,000, with a few isolated exceptions, the plane-coordinate systems devised for the different states may be used without the application of any scale-factor whatever. However, where more accurate work is required, provision is made for the application of a scale-factor, obtained by interpolation in tables, which give any desired accuracy. In many of the states only a single system of coordinates was required. The number of coordinate-systems in a State, as well as the projection selected for the different systems, depend largely on the shape of the State, its size, and whether its major axis is in a north-and-south or east-and-west direction.

Cooperative work

The United States Coast and Geodetic Survey has cooperated with many governmental agencies in the extension of control-work and associated activities during the year. It cooperated with the Bureau of Reclamation in extending triangulation and leveling of better than first-order accuracy around Boulder Dam and vicinity for the purpose of studying possible deformation of the structure itself or of the Earth's crust as a result of the colossal load caused by filling the basin. The triangulation and leveling were executed at about the time that the storage of water began and it is understood to be the intention of the Bureau of Reclamation to have the observations repeated in the course of about three years, when it is expected that the reservoir will be filled. It is interesting to note in this connection that the leveling required in this study was approximately 1000 miles. The triangulation did not cover such a broad territory but did include a rather large number of observations and measurements in and about the dam.

The Survey has also cooperated with the Advisory Committee in Seismology of the Carnegie Institution of Washington in the extension of triangulation and leveling in California for the purpose of earthquake-investigations. Last summer some 1800 closely spaced bench-marks were set along nine lines of levels crossing normal to eight fault-zones in southern California.

The elevations of these bench-marks were determined by first-order leveling and were tied into the national vertical control-net. These monuments will be coordinated with the horizontal control-net as soon as funds are available. The monuments close to the fault-zones are spaced at intervals of 100 feet, and the intervals are increased gradually to the outer limit of the work so that at a distance of about five miles from the fault-line they are spaced approximately 500 feet apart.

Lines of levels have been extended in and around San José, California, for the purpose of investigating a settling of the Earth's crust in that region first noted sometime about 1930. Altogether about 175 miles of leveling are involved in this area. The original leveling was done in 1912 and 1920, and in the winter of 1931-32 some releveling in that region for the purpose of strengthening the general net showed changes in elevation quite in accord with the reports which had come from local engineers. As a result of this discrepancy and in accordance with the recommendations of Dr. Bailey Willis and Dr. C. F. Tolman of Stanford University, California, the United States Coast and Geodetic Survey cooperated with them on four successive occasions in rerunning levels over the same lines. Similar field-work is now in progress about San José.

The Bureau has been requested to extend such first-order leveling in the vicinity of Helena, Montana, as may be required to determine any possible movements resulting from the earthquake in that region last winter. The necessary funds have been provided for this work and arrangements are now being made by a field-party to begin work soon.

An officer is now engaged in the extension of lines of levels in the vicinity of Galveston, Texas, in cooperation with the District Engineer. About 300 miles of leveling is involved in this project.

The United States Coast and Geodetic Survey has cooperated with the Tennessee Valley Authority during the past two years in the extension of horizontal and vertical control in the Tennessee Valley Basin to the 25-mile interval, and at present an officer is extending lines of levels as required to strengthen the net in that region.

Work has been carried on in cooperation with the Soil Conservation Service in Arizona and additional work is proposed in New Mexico and Wyoming within the next few months. It is anticipated that the Soil Conservation Service may carry on a rather extensive surveying and mapping program under recent authorization of Congress, in which it is understood that surveying and mapping organizations may be called upon to furnish the necessary cooperation to the ultimate end of obtaining the required maps.

A gravity-party has been in continuous operation in Cuba, Florida, Pennsylvania, and southern New England since April 1, 1935. The work in Cuba was done in cooperation with the Atlantic Refining Company of Cuba and the stations in the vicinity of Bethlehem and Bradford, Pennsylvania, were determined at the request of Prof. Benjamin L. Miller of Lehigh University and Paul E. Torrey of the Sloan and Zook Company, Bradford, Pennsylvania. The stations in Rhode Island and Connecticut were requested by Prof. Charles W. Brown of Brown University and Prof. Chester R. Longwell of Yale University. The Bureau has recently completed a gravity-survey in Florida through a cooperative arrangement with the Internal Improvement Board of the State of Florida. The State furnished the funds for this work which included determinations at 21 stations. The total number of stations for the year is 129, making a total for the country and adjacent islands of 920 stations.

Through the interest of Dr. E. A. Eckhardt of the Gulf Refining Company, we have recently been furnished the results at 83 of their gravity-stations located in the Gulf states of Texas, Louisiana, Mississippi, and Oklahoma. These will be of great value to this Bureau in studying the isostatic conditions in that area.

Our astronomical field-work requires excellent time-determination in order to obtain the highest degree of accuracy from our observations. In the application of radio to the time-service within recent years it has been possible not only to increase the accuracy of our determinations of longitude but also to accomplish more field-work in a given period of time. The United States Naval Observatory has always cooperated with the United States Coast and Geodetic Survey to the fullest extent in furnishing time-signals to meet the requirements of the Survey, and within the last year two additional broadcasts of signals have been inaugurated, greatly improving this part of their service and facilitating our work tremendously. We express the hope that the time is not far distant when it will be possible to obtain accurate broadcasts of time from the Naval Observatory at even more frequent intervals.

Through the cooperation of the National Bureau of Standards the United States Coast and Geodetic Survey has been able within the last three years to obtain precision theodolite-circles for nearly all of its first- and second-order instruments. The importance of this work and the credit due the National Bureau of Standards for its cooperation can only be fully understood when one realizes the difficulty of obtaining high-grade theodolite-circles of that type through the usual commercial channels.

The regular observations at the variation-of-latitude observatories at Ukiah, California, and Gaithersburg, Maryland, have been continued throughout the year. The records for the observations are being sent directly to the Chief of the Central Office, International Latitude Service, which is now held by Senor Luigi Carnera.

Satisfactory progress has been made in the adjustment of the triangulation into the North American datum of 1927 and also the fitting of new lines of levels to the first-order net as adjusted in 1929.

Conclusion

A continuing program for the extension of triangulation, leveling, astronomical observations, base-measurements, gravity-determinations, observations for studying variation of latitude, etc., is urgent in order that there may be avoided the multiplicity of datums, overlapping of surveys, lack of coordination, general confusion, and waste which will result until our control-framework receives more general distribution through the country. The predominant need at present is for maps. These are used for innumerable purposes, but particularly for any problems where the elevation, contour, or boundary-limitations of any section of the Earth's surface is considered. To say that this work should receive early attention so that it will be of the greatest public value is only another way of saying that "a stitch in time saves nine."

However, aside from the primary value to mapping, there are many great advantages to be obtained by the use of such surveys, both in the engineering and scientific fields. In the engineering field the extension of these control-surveys are of inestimable value in the construction of roads, highways, railroads; for irrigation, flood-control, drainage, reforestation projects; for the extension of gas and oil pipe-lines, transmission-lines, development of minerals and oil-deposits, and in fact for all large-scale operations embodying considerable areas of land. In the scientific field the surveys furnish invaluable information in the search for hidden structure in regions of deposits of oil and minerals, for the determination of the figure of the Earth, for the study of certain refracting conditions in the Earth's atmosphere, and for many other purposes. They are a prerequisite to making a national inventory of our natural resources to the end that they may be conserved, protected, and used in the manner to be of the greatest good to our citizens.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GEODETIC WORK IN MEXICO DURING THE YEAR 1935

Manuel Medina

Geodetic triangulation--In continuing the extension of projected triangulation in the Republic, the work done in 1935 was limited to that part of the arc along the 102° meridian contained in the State of Zacatecas, with the object of basing upon it the geographic surveys which are being made in that State for the construction of its map. Observations were also continued on the projected arcs along the Lerma and Santiago rivers, with the purpose of connecting this triangulation across the states of Jalisco and Nayarit with the chain already observed in the State of Sinaloa.

The geodetic parties which had to observe angles were able to make use of the last months of the year only. Atmospheric conditions were not very favorable due to prolonged rain and continuous meteorological disturbances during the year.

In the State of Zacatecas 22 triangulation-stations were occupied, using Wild theodolite of 0".2 angular approximation on both circles. The observations had a weight of 24; that is to say, each line was observed 12 times with the instrument direct and 12 with the instrument reversed. The mean length of the sides of this arc was 70 km; the mean probable error of a direction repeated 12 times was ± 0".30 and finally, the mean error of closure of the triangles was ± 2".0.

Two observing parties worked on the arc along the Lerma and Santiago rivers. Each party was provided with a Wild theodolite and electric signal-lamps. The first party observed the angles of that part of the arc contained in the states of Guanajuato and Michoacán. The mean length of the sides of this part of the arc was 40 km. The mean probable error of the direction repeated 12 times was ± 0".55 and the mean error of the closure of the triangles was ± 2".28.

The second party occupied those stations located in the State of Jalisco. They observed some lines more than 100 km long. The mean probable error of a direction repeated 12 times was ± 0".40 and the mean error of closure of the triangles was ± 3".0.

Base-measurement--In connection with the last arc mentioned a geodetic base was measured in the vicinity of Guadalajara, Jalisco, the length of which was approximately eight km. The measurement was made with 24-meter invar wires Nos. 26, 33, and 37. The base was divided into 11 sections, each one of which was measured in a day.

As in other bases measured by this Commission, the invar wires were supported on prisms especially mounted on tripods of wood, which were lined in between the end-points of each section. The invar wires were kept under a tension of 10 kilograms. At the same time the measurement was made, levels were run on the edges of the prisms, which supported the invar wires, for reduction to the horizontal.

The first calculation of the Guadalajara base reduced to sea-level gives the following results: Length 8009.731 meters, relative probable error 1/8,000,000. The base was connected to the arc by two expansion quadrilaterals which gave a strong tie.

Geodetic astronomy--A precise determination of astronomical latitude and longitude was made in the City of Guadalajara and the astronomical station was tied trigonometrically to the triangulation in order to make it possible to compute preliminary geodetic coordinates for immediate application to the map of the State. The geodetic coordinates of these points will be referred to the datum-point at Meades Ranch (United States) as soon as this arc is tied in and adjusted to the general net of the country.

The coordinates obtained at the astronomical station and their probable errors are: Latitude, 20° 40' 31".71 ± 0".09; longitude, 103° 23' 11".30 ± 0".83.

For immediate cartographic use secondary astronomical stations were established in the following places in the State of Michoacán: Los Reyes, Zamora, Cotija, and Jiquilpan. The first two of these stations were determined with a zenithal meridian telescope and a small number of observations, and the last two were determined with an altazimuth so as to obtain maximum probable errors of ± 1".

Gravity--The gravity-program of the country was continued by making a circuit of observations including the following places: Tacubaya, Distrito Federal (base-station); Puerto México, Veracruz; Matias Romero, Oaxaca; Tonalá, Chiapas; Tuxtla Gutierrez, Chiapas.

The places named are in the Isthmus of Tehuantepec, to the south of the volcanic line, and the results of the computations have a great deal of interest for the study of the distribution of the anomalies in our country. At the same time, the last station established in Tuxtla Gutierrez, near the frontier of Guatemala, Central America, will serve as a base-station or point of departure for the gravity-circuits which are to be observed in Central America through the efforts of the Pan-American Institute of Geography and History. The results obtained for these four stations were as follows: Puerto México, Veracruz, 978.530 ± 0.0010; Matias Romero, Oaxaca, 978.419 ± 0.0007; Tonalá, Chiapas, 978.373 ± 0.0016; Tuxtla Gutierrez, Chiapas, 978.293 ± 0.0005.

Precise leveling--We have completed in the course of the year a line of levels between Tacubaya, Distrito Federal, and Cuernavaca, Morelos, along the road which goes from Mexico City to the Port of Acapulco, Guerrero. This leveling is tied with the line from Mexico City to Veracruz, so that when it is finished it will be interoceanic and there will be new data for determining the relative levels of the Gulf of Mexico and the Pacific Ocean.

This leveling was done with a Gurley level, United States Coast and Geodetic Survey type, and two rods 3.2 meters long, each provided with its thermometer and spherical levels. The maximum divergence between the forward and backward running of the section is 3 mm $\sqrt{K}$, and the results obtained in the 90 sections which made up the line of levels from Tacubaya to Cuernavaca were as follows: Maximum length of section, 1985.36 meters; mean length of section, 840.00 meters; maximum error between the backward and forward runnings, ± 4.00 mm; mean error (mean of the errors between the backward and forward runnings), ± 1.21 mm. The orthometric elevations of all bench-marks were computed and each monument marked with its elevation.

In the Port of Acapulco the study of mean sea-level was continued with a "Lallemand" tide-gage which records graphically.

FIG. I—TAPE-STANDARDIZATION ROOM

Topography--In the State of Zacatecas a chain of triangles was measured along the Juchipila Canyon and the arc was tied in with the geodetic triangulation which crosses the State of Jalisco. This work was done in order to provide control-points for the topographic survey of this region where at present surveys are being completed by other departments which are important to irrigation.

The angles of this chain were measured with a Wild theodolite with one-minute angular approximation, on which one may estimate one-tenth of a division or six seconds. The mean length of the sides observed is 25 km; the mean probable error of a direction repeated six times was ± 3".0 and the mean error of closure of the triangles was ± 17".0.

Stereoscopic photography--The stereophotographic survey was completed in the State of Morelos. This survey was tied in to the geodetic and topographic net previously measured. Thirty-eight bases were measured and located. At the ends of these bases horizontal photographs were taken of the terrain with the special Zeiss camera C/3 b. At each camera-station three photographs were taken for each 30°, the camera being oriented mechanically for this operation. This gave three stereoscopic pairs for each base.

In accordance with the cartographic program which this Institute has formed, the map of the State of Morelos will be constructed to a scale of 1:75,000 with contour-lines for every 25 meters.

Comparison of tapes--We have made several adaptations of our comparator in order to facilitate and expedite the standardization of metric tapes and invar wires employed for measurements of lengths by this office and by other official bureaus. With this in view we made a remeasurement of the standard sections 0-4, 0-8, 0-20, 0-24, 0-25, 0-48, 0-50, and 0-100 meters of our comparator and established other auxiliary marks on the west wall of the gallery on small brackets firmly embedded in the wall and referred to the marks on the floor. We intend to use these marks, without the aid of a microscope, for the standardization of tapes sent in by the public which require a minimum precision.

Cartography--The work of this section is divided into two classes of activity: (a) The publication of geographic maps of the country formed with the best data available from various authorities; (b) the making of exact maps from the results of the geodetic and topographic surveys themselves.

With respect to (a) we are now revising and editing the "Geographic atlas of the Mexican Republic," which is made up of maps of the states on various scales; with respect to (b) we are working upon the atlas of maps of 1:500,000, which is made up of squares of 2° of latitude by 3° of longitude. These squares, besides their other applications, will constitute a part of the world map of 1:1,000,000, this being done by uniting four contiguous squares and reducing to half the scale.

Finally, we are now working on the wall maps of the states of Morelos, Sinaloa, and Zacatecas, to a scale of 1:75,000, 1:200,000, and 1:500,000, respectively.

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AN INTERPRETATION OF GRAVITY-ANOMALIES IN TERMS OF LOCAL AND REGIONAL GEOLOGIC STRUCTURES

G. P. Woollard

Introduction

That there exists a relationship between gravity-anomalies and geologic structure has long been suggested by G. K. Gilbert, J. Barrell, David White, William Bowie, and many others. White [see number 1 of "References" at end of paper] observed that negative anomalies were found over synclines, and that positive anomalies occurred over anticlines. Bowie [2] and Miller [3] both pointed out that positive anomalies were found in regions of exposed pre-Cambrian rocks, and that negative anomalies were observed over Cenozoic sediments.

This reflection by gravity-anomalies of both structure and the kind of rock underlying a station has been further verified by the great mass of gravity-work that has been done in recent years. However, it has been found that it is not the structure of the superficial rocks that is reflected by gravity, but rather the structure of the underlying crystalline basement, and that the relation to kind of rock is a function of the density of the rock. Just as the early Bouguer anomalies [4] were found to reflect the surface-topography until they were isostatically compensated for elevation, the present anomalies mainly reflect the configuration of the crystalline basement plus the character of the material overlying it. Chamberlin [5] has already demonstrated that if a geologic factor of compensation is introduced whereby the actual densities of the geologic units underlying a station are considered rather that a set value of density for the entire geologic column as is used at present, much of the observed anomaly is eliminated.

That the structure of the crystalline basement-rocks should be reflected in the gravity-values is undoubtedly a result of their high density in comparison to that of the light sedimentary material overlying them. Where the crystallines are exposed at the surface,there is a "high" on the gravity-profile. Where they are deeply buried under light detrital material, there is a "low" on the gravity-profile. That the structure would be masked when a structural basin in the crystallines is filled with high-density material, such as a sedimentary iron of the Lake Superior type, is to be expected, and that this may be the case in the Michigan Basin will be indicated later.

In general though, it is here suggested that basins and troughs in the basement-complex are revealed by the occurrence of negative anomalies over them. The only other structural features which would be reflected by negative anomalies, as far as the writer is aware, would be salt-bodies occurring either as intrusive domes or as thick basin-deposits. In such cases there would be a deficiency in mass as a result of the low density of the salt in comparison to the material adjacent to it which would cause the negative anomaly.

To avoid confusion it must be pointed out that the terms "negative anomaly" and "positive anomaly" as here used do not refer to an actual numerical negative or positive value as regards sign, but rather to the relative value of any anomaly as compared to an adjacent anomaly. The actual value of the particular anomaly might be either negative or positive. For example, in plotting a gravity-profile across a salt-dome it might be found that every station showed a positive numerical value, yet the gravity-profile when drawn would indicate a "high" or "positive" value which graded into a marked "low", the "negative"-anomaly area resulting from the mass of intruded salt, and then went into another "high" marking the other flank of the intrusive. The structure is revealed just as adequately as if the actual anomaly-values had run in sign from positive to negative. The case here used is not a hypothetical one, for the above conditions have been revealed by detailed gravitational studies of many deeply buried salt-domes of the Gulf Coast Field.

Positive anomalies are suggestive of (1) an actual exposure of dense crystalline or metamorphic rocks, (2) the presence of granitic intrusives near the surface, or more dense ultrabasics at depth, (3) the filling of a structural basin with high-density material, (4) the presence of an ultrabasic sill in a synclinal basin filled with normal sediments such as the Duluth Gabbro lopolith which gravitationally completely masks the Superior Syncline, or (5) an extra thickness of normal sediments in a region underlain by a great thickness of light material as is commonly observed on the flanks of salt-domes.

Gravity-data from the Beartooth-Bighorn Region

From the above considerations it is apparent that for any adequate interpretation of gravity-anomalies some idea on the geology of the region under consideration is indispensable. It is hence not surprising that so little correlation has been made between gravity-anomalies and geologic structures except for local areas. For in regions of known geology there is often very little gravity-control, and in regions of good gravity-control the geology is frequently hazy. However, through the cooperation of the United States Coast and Geodetic Survey a test-area where both the gravity and geology are known in good detail has now been studied [6 and p. 1 of 1]. This region, including part of the Beartooth and Bighorn mountains lying in Wyoming and Montana, was not one picked for its simple structure. It is a part of the Rocky Mountain System and has been subjected not only to folding but also to intense major faulting.

The map of Figure 1 is one constructed with contours connecting points of equal anomaly-value. With no knowledge of the geology of the region one would be impressed that marked structural features are present. What these are is seen when gravity-profiles along section A-A and B-B are compared with the geologic profile.

In a broad way the configuration of the gravity-profile parallels the configuration of the crystalline basement-rocks. Where the crystallines are near or actually at the surface as in the Beartooth and the Bighorn mountains, the gravity shows a marked "high" and close surface-parallelism. Where the crystallines disappear beneath the sediments of the Bighorn and the Powder River basins, the gravity follows the same general configuration. However, the parallelism is not so marked as here there is a considerable thickness of sedimentary material intervening between the observation-station and the basement-rocks. The density of this material is sufficient to modify the actual configuration of the basement as here shown. If the basin had been filled with material of a much lower density, as water, a closer parallelism would be expected. Similarly if the basin had been filled with a material of such a density as to equal that of the crystallines, the gravity-profile would parallel the surface-topography, and if the fill-material had been of a much higher density, the basins would have been represented by "highs" on the gravity-profile. The above postulations are supported by other areas in which, locally at least, there is sufficient evidence to justify them. The main control always appears to be the density of the material immediately underlying the station.

As previously mentioned, Chamberlin [p. 1 of 1] recomputed the anomaly-values in the Beartooth-Bighorn Region considering the geologic columns and their actual distributed densities. On the map (Fig. 1) are indicated his values immediately under those obtained by the United States Coast and Geodetic Survey for the same stations. Gravity-profiles for the two sets of values show that there is a tendency to reduce towards zero both the negative and positive anomalies, indicating that much of the present observed anomaly is the result of the lack of consideration of the actual densities involved.

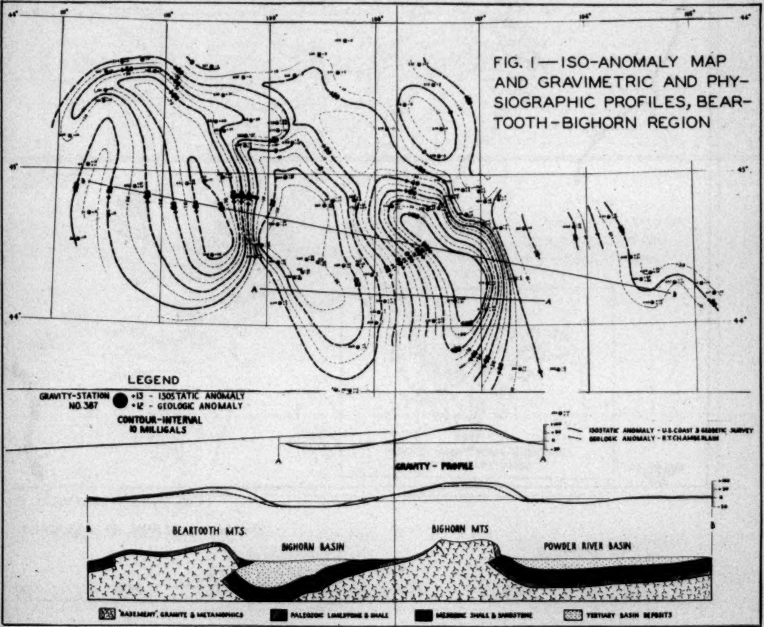


FIG. 1—ISO-ANOMALY MAP AND GRAVIMETRIC AND PHYSIOGRAPHIC PROFILES, BEARTOOTH-BIGHORN REGION

LEGEND
GRAVITY-STATION NO. 387
+13 - ISOSTATIC ANOMALY
+12 - GEOLOGIC ANOMALY
CONTOUR-INTERVAL 10 MILLIGALS
ISOSTATIC ANOMALY - U.S. COAST & GEODETIC SURVEY
GEOLOGIC ANOMALY - R.T. CHAMBERLAIN
A
A
B
B
GRAVITY - PROFILE
BEARTOOTH MTS.
BIGHORN BASIN
BIGHORN MTS
POWDER RIVER BASIN
"BASEMENT", GRANITE & METAMORPHICS
PALEOZOIC LIMESTONE & SHALE
MESOZOIC SHALE & SANDSTONE
TERTIARY BASIN DEPOSITS
44°
45°
+100
+50
0
-50

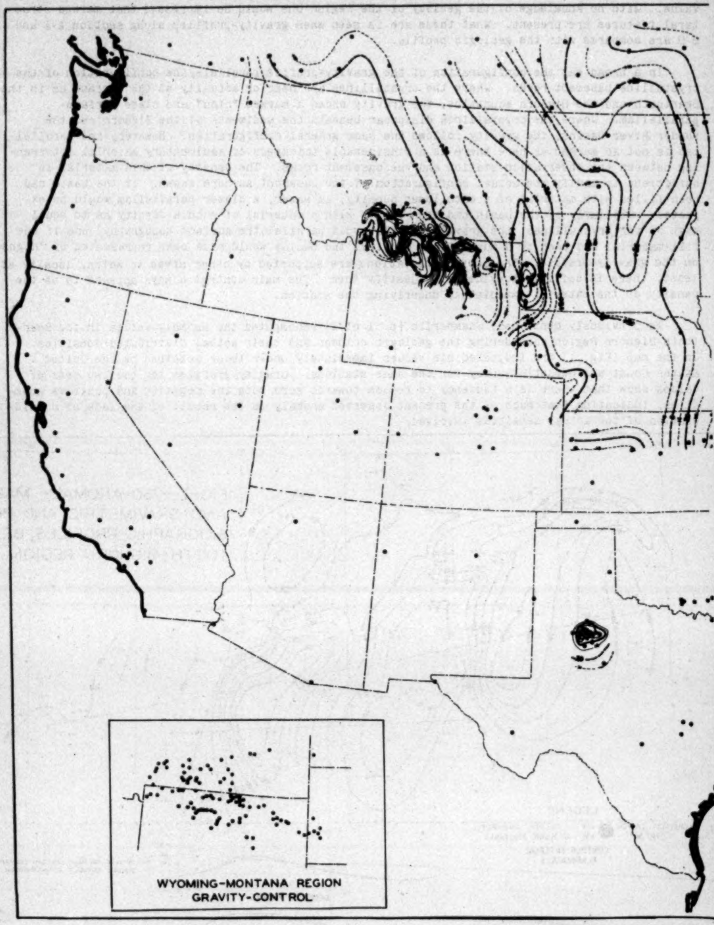
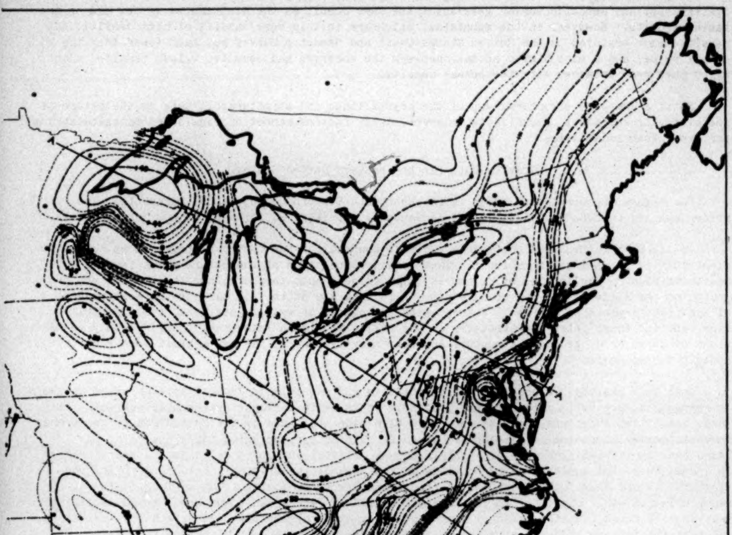

WYOMING-MONTANA REGION
GRAVITY-CONTROL

FIG. 2—ISO-ANOMALY

CONTOUR-INTERVAL 10 MILLIGALS

SCALE IN MILES

0 200 400 600 800 1000


A
A
LEGEND
• =GRAVITY-STATIONS
—— =GOOD CONTROL
- - - =POOR CONTROL
G.P. WOOLLARD
PRINCETON
1936

MAP OF UNITED STATES

60-KILOMETER COMPENSATION

SCALE IN KILOMETERS
0
400
800
1200
1600

It just so happened that the average density-value employed at the present by the United States Coast and Geodetic Survey gave about the same result as the distributed values did on the basin deposits. However, in the mountains, which are in this case massifs of high density, the density-value employed by the United States Coast and Geodetic Survey was much lower than the actual value, and a much higher anomaly between the observed and computed values resulted than would have been obtained with the actual density.

Until a complete structural map of the crystallines and stratigraphic data on the nature of the overlying sediments is available, however, these factors cannot be considered in calculations for other than local areas.

Gravity-data for the eastern United States

The degree of correlation shown in the Beartooth-Bighorn Region was so marked that the writer was led to construct a tentative iso-anomaly map (Fig. 2) for part of the United States.

On the Eastern Seaboard there is a variable control for the most part regarded as sufficient to reflect regional structures. That detail correlation of the nature shown for the Beartooth-Bighorn Region can not be had is quite evident when this area and its control are projected on the scale of the map of Figure 2. Also that any attempt to contour the western part of the country would be futile is evident when the number of gravity-stations, their distribution, and the known intricate structure of the region are taken into consideration. Only in regions of known broad geologic structure and fair gravity-control has any attempt been made to contour the anomalies.

That this gravity-picture is at best tentative and possibly in considerable error in places is recognized, but until more data are available it is believed to be essentially correct. In three localities additional gravity-data have been made available by the United States Coast and Geodetic Survey since the completion of Figure 2. The writer, on using these new data, has found that in the Lehigh Region of Pennsylvania--a critical one as it represents a sharp change in trend-lines--the addition of 23 stations did not change the original contouring in any particular. It did show that the indicated trough was deeper by adding a -50 contour to the already existing -40. Similarly in the Bradford Region of Pennsylvania and New York 20 additional stations indicated that the existing high went one contour higher than had originally been shown and that the feature probably extended up into an area purposely left blank due to lack of in-

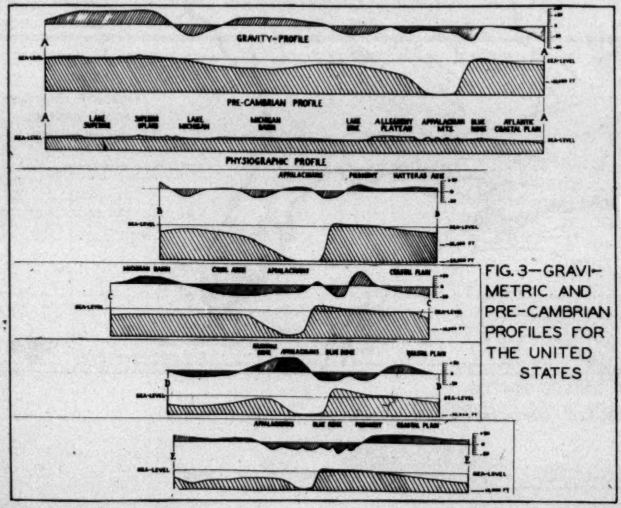

A
GRAVITY-PROFILE
A
SEA-LEVEL
SEA-LEVEL
PRE-CAMBRIAN PROFILE
A
LAKE SUPERIOR
SUPERIOR UPLAND
LAKE MICHIGAN
MICHIGAN BASIN
LAKE ERIE
ALLEGHENY PLATEAU
APPALACHIAN MTS.
BLUE RIDGE
ATLANTIC COASTAL PLAIN
A
SEA-LEVEL
SEA-LEVEL
PHYSIOGRAPHIC PROFILE
APPALACHIANS
PIEDMONT
HATTERAS AXIS
B
B
SEA-LEVEL
SEA-LEVEL
MICHIGAN BASIN
APPALACHIANS
COASTAL PLAIN
C
C
SEA-LEVEL
SEA-LEVEL
APPALACHIANS
BLUE RIDGE
COASTAL PLAIN
D
D
SEA-LEVEL
SEA-LEVEL
APPALACHIANS
BLUE RIDGE
PIEDMONT
COASTAL PLAIN
E
E
SEA-LEVEL
SEA-LEVEL

FIG. 3—GRAVIMETRIC AND PRE-CAMBRIAN PROFILES FOR THE UNITED STATES

formation of even the broadest kind. Likewise, in the region to the south of Lake Okechobee, Florida, a more complete gravity-net shows that the original contouring is essentially correct, and that a hitherto unsuspected high exists in an area indicated on Figure 2 as being a neutral one. With such verification of regional structures by detail gravity-work and, what is more remarkable yet, with so little conflict even in detail, the writer feels justified in correlating known geologic structures with the gravity as here depicted.

Marked structural features, as the trend of the Appalachian Mountain System extending from Alabama up through the St. Lawrence Valley, the Adirondacks (an area of anorthositic intrusives in northern New York), the Cincinnati Arch in Ohio and Indiana, the Nashville Dome in Tennessee, the Ozarks in Missouri and Arkansas, the Gulf Coast Syncline, the Michigan Basin, the pre-Cambrian exposures in the Superior Uplands, and at the Fall Line on the Atlantic Seaboard, are clearly discernible. Other features of which we have little knowledge as to their exact meaning are the areas of high anomalies around Washington, Philadelphia, and Hoboken [7,8]. Apparently they are reflections of either granitic intrusives near the surface or else more basic intrusives at depth.

Geographically some of the features do not show good correlation with their geologic counterparts. The Ozarks, for instance, show their greatest mass to lie to the west of what we would expect from present knowledge of the local areal geology. As no gravity-stations are had where the crystalline rocks of this region are exposed at the surface, and as there is a general scarcity of data in this instance, the picture as drawn is more than likely in considerable error. However, the occurrence of what appears to be a trough-condition in the middle of the Piedmont, which is regarded as being exposed crystalline pre-Cambrian rocks and where there is good gravity-control, calls for speculation.

It will be noted that the "trough"-feature extends all along the Piedmont Belt from Georgia to New Jersey, and appears to merge northward into the region that was involved in the Taconia Revolution. Whether this belt is continuous as drawn or actually occurs in two distinct parts is questionable though the former appears the more probable. This feature will be considered in more detail when profile-sections along the lines indicated are shown.

Considering the country as a whole it will be noted that there exist two definite trend-lines as revealed by the gravity, one trending northwest and the other, nearly normal to it, trending in a general northeast direction. The relation of the northeast trend to the Appalachians and the line of domes extending from the Adirondacks through the Nashville Dome is marked. The relation of the northwest trend to marked geologic features is, however, not so apparent. It is of considerable interest to note though that these two trends correspond with the metallogenetic alignments which have been noted by Ransome [9] and Sampson [10]. The more marked of these alignments are in a northwest direction running from Seattle, Washington, to the Black Hills, and from Los Angeles to Brownsville, Texas, and in a northeast direction from the Black Hills to Los Angeles. These same trends appear to have a submarine reflection in the two partial structures indicated in the Gulf of Mexico. The northeast-trending one perhaps represents a continuation of the crystallines along the Atlantic Coast after having dipped under the Gulf Geosyncline. If such is the case, future gravity-data would probably reveal Appalachian type structure carrying on down into Mexico on this same general trend. The significance of the northwest-trending structure is questionable, but it is of interest to note that it does appear to tie in geographically with a similar trending structure in the basement-rocks of the Gulf Coast as indicated by the preliminary structural map of the basement-surface just prepared by the American Geophysical Union's Special Committee on the Geophysical and Geological Study of Continents.

In every case where definite corroborative evidence exists, the gravity appears to fit the geological structural conditions extremely well. The profiles of Figure 3 comparing the gravity along the indicated sections with the crystalline basement-surface as it is known at the present will further serve to show this relationship and also bring out other features.

Consider profile A-A of Figure 3, which depicts the gravity-condition, the crystalline basement-surface, and the general physiography. It is seen that on the west fairly good correlation is had between the gravimetric and the crystalline outcrop in the Superior Uplands. Progressing eastward it is to be noted that, whereas both Lake Michigan and Lake Erie are indicated by gravimetric lows, Lake Superior is not reflected. Although no actual gravity-observations were taken on the lakes, it is suggestive that the deficiency in mass appears to exert a force on the land-stations adjacent to them sufficient to give gravity-troughs despite the fact that to our knowledge the crystallines are actually rising northwestward under Lake Erie. The lack of such a relation, if it can be regarded as characteristic on the strength of present data, in the case of Lake Superior is a result of the presence of the intrusive Duluth Gabbro which as a result of its high density masks the feature.

That the Michigan Basin, on the strength of present gravity-data, should show up as a positive anomaly-area is interesting inasmuch as geologic information as revealed by well-logs indicates the presence of no abnormally dense sediments to a depth of 5000 feet below the surface. The presence of various salt-horizons,on the contrary, suggest that the area would be a markedly negative one. Therefore, any explanation postulated will have to be of a hypothetical nature. There are two relatively probable explanations, namely, that the region is underlain at depth either by an intrusive sheet of the nature of the Duluth Gabbro, or else by abnormally heavy sediments perhaps similar to those of the iron formations in the Lake Superior Iron Region. Of the two theories the second would appear the more probable considering the fact that the gravity-profile conforms to the shape of the basin, that is, indicating a marginal feather-edge with thickening towards the center. However, these are merely suggestions, and it must be borne in mind that later gravity-data may greatly alter this picture, for it is a region at the present with none too good control.

East of Lake Erie an elongated gravity-"high" extends into central Ohio from a little south of the Adirondacks. This feature is paralleled on the east by two trough-like forms before rising to what is evidently an actual outcrop of the crystallines from under the Coastal Plain sediments. It is seen that here the gravity-profile fails to show any agreement with that of the crystallines, this same lack of agreement following along on each section. It is suggested that perhaps the first trough, the western one, represents the Appalachian Trough proper, the eastern one, as seen on section A-A, the Triassic Fault-Trough which runs from Pennsylvania to New York. However, there appears no good geological excuse for carrying this trough on southward, as it occurs in a region of actual surface-outcrop of the crystalline rocks, and as previously mentioned it also appears to extend northward into the Taconic region of New Hampshire and Vermont. Does this feature signify in the south a trough of light sediments which is obscured by infolding, or which has been covered by an overthrust sheet? Or does the Piedmont Region actually represent two features, one being the actual pre-Cambrian crystalline basement-rocks which outcrop at the Fall Line from under the Coastal Plain sediments to continue for a short distance and the other a trough of metamorphosed early Paleozoic sediments which, despite their metamorphism, have a sufficient density-differential to show up on the gravity-profile? If such a condition exists, is the western boundary of this trough an actual prong of the crystalline basement as is seen separating the Triassic sediments from the Appalachian Trough in New Jersey and Pennsylvania, or was there originally just the one synclinal feature with perhaps the Carboniferous granites cutting off the material on the eastern side so that two troughs now appear to be reflected?

This region has long been one of geologic controversy, and it appears that more complete gravity-data will give material evidence on the situation.

Another problem that is raised by the gravity is, exactly what is the condition represented by the Hatteras Axis? Apparently a ridge of the basement-crystallines here projects eastward, whereas elsewhere along the coast the surface of the crystallines has a fairly gentle and even seaward dip.

Other features as the Nashville Dome on section D-D give good correlation although it would appear here slightly out of geographical position. Probably this is a result of two variables, neither of a hard and fast control, the information on which the crystalline basement-map [11] was built and the gravity-data.

The significance of the anomalies in the Appalachian Region on section E-E is not certain, but it is suggestive of an actual close folding of the basement-rocks or else basement-faults, or more probably, especially on the eastern side, of the presence of numerous granitic intrusives which are known to be present in this general area.

Gravity data for the Gulf-West Indian Region

The Gulf-West Indian Region is one in which there are considerable gravity-data. It is a region of varied structure, and it is believed possible with even the present gravity-control to show that this structure is clearly reflected in the gravity.

Considering the Gulf Region (Fig. 4), it will be noted that there is a syncline indicated which, although it does not conform in detail to that postulated by Barton and Hickey [12], is believed to be essentially correct for the present data. Progressing offshore an area of in-

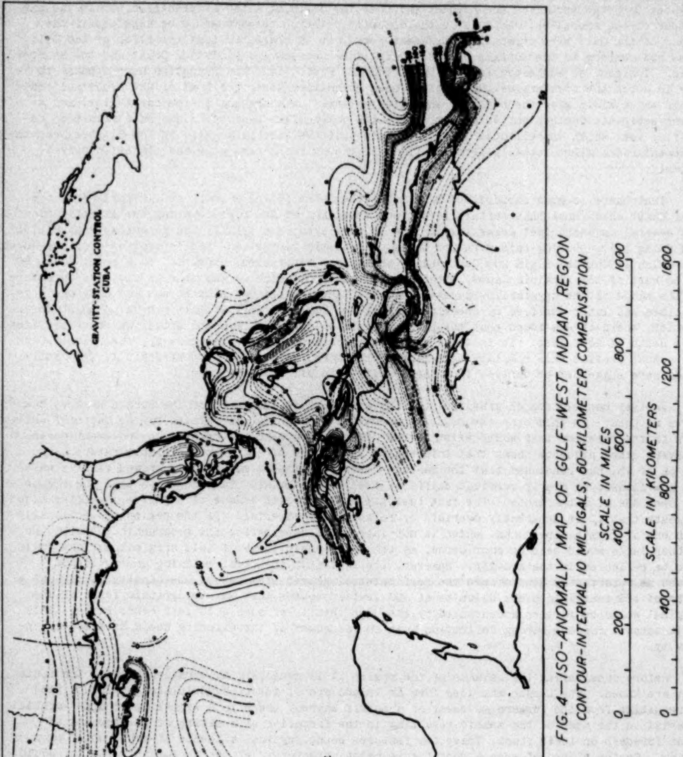

GRAVITY-STATION CONTROL
CUBA
W
E
S
SCALE IN MILES
0
200
400
600
800
1000
SCALE IN KILOMETERS
0
400
800
1200
1600

FIG. 4—ISO-ANOMALY MAP OF GULF-WEST INDIAN REGION
CONTOUR-INTERVAL 10 MILLIGALS, 60-KILOMETER COMPENSATION

creasingly positive anomalies is found. Hess [13] has called attention to the fact that in the Sigsbee Deep the anomalies are highest and that the depth of water apparently controls the magnitude of the anomalies. As this is the opposite relation to what would be expected if the floor of the Gulf were crystalline basement-rocks, it is suggested that the floor of the Gulf does not conform to the surface of the crystallines between the Louisiana Coast and the Sigsbee Deep. Instead, as suggested earlier by Barton and Field [14], the situation here appears to be one in which the crystalline basement has been downwarped under the load of the synclinal sediments which would give the negative anomalies observed on shore and at the coast-line, and as these sediments feather out in deeper water, the crystalline basement rises as a result of relief of load which is reflected in increasingly positive anomalies until in the Sigsbee Deep the basement-rocks might actually form the floor of the Gulf and here give the highest observed anomaly.

That there is good support for such a hypothesis is proved both by well-records from the Gulf Coast which show that certain formations which are at the surface along the Atlantic Coast are several thousand feet below the surface in this area, and also by the recent work of Miller and Ewing [15]. During this work Dr. Ewing ran seismic refraction- and reflection-profiles across the Atlantic Coastal Plain and Continental Shelf from Petersburg, Virginia, to a point about 80 miles east of the Virginia Capes, obtaining results from which he was able to plot the curvature in the slope of the crystalline basement-rocks. That the feature plotted was actually the crystallines was later verified by checking against the log of a well at Fort Monroe, a point on the section, where it was found that the plotted position diverged from the actual by about ten feet at a depth of 2000 feet. It is to be noted that in this instance the gravity, the seismic, and the actual profile show complete agreement. Therefore, this lends more strength to the conditions here suggested as derived from the gravity-data off the Gulf Coast.

Another correlation of gravity-intensity and depth is indicated in the Bahama Area to the north of Cuba. In this case the negative anomalies apparently are related to the depth of water. This is the relation that would exist if the ocean-bottom were the crystalline basement-rocks. However, other evidence shows that this region is not one of quite such a simple nature. Hess [p. 52 of 13] has concluded that the Bahaman "deeps" represent subaerially eroded valleys which are now flanked by nearly vertical cliffs of reef (?) material. This suggests that the region has been one of submergence. The fact that the entire region is one of negative anomalies also suggests that it is apparently overlain by rather light material. If the region had originally been one of crystalline rocks, which is not improbable considering its geographic position, no further facts would need be considered, as the topographic forms of this original surface would then be reflected in the gravity. However, the fact that an actual well-log on Providence Island as reported by Hess showed the reef material graded from porous low-density calcite at a depth of 165 feet into dense dolomite at 390 feet indicates that any topographic forms of the original would be further accentuated by the high density of some 4000 feet of dolomite. This would account for the strong delination seen on the edges of the existing deeps as shown by the gravity.

Before considering the balance of the region it is necessary to consider briefly the facts that are known. The Lesser Antilles form an island arc of the type postulated by Tokuda [16] as resulting from the forward movement of a massif whereby there is a wrinkling of upper crustal material on the nose of the massif resulting in the formation of a string of islands and an ocean foredeep on their front, these two features being physical evidence of the crustal corrugation. On the flanks of such a massif en echelon structures, either as folds or faults, would develop as a result of horizontal shear. That this is apparently the situation here is seen from the plan of the island arc, the actual occurrence of deeps along their fronts, and the report by Taber [17] of marked en echelon faulting along the south end of Cuba where the arc-structure and apparently the deeps end. The structural pattern therefore offers perfect agreement with such a theory. Further, Vening Meinesz [18] in investigating the gravity-conditions in the East Indies found a band of strong negative anomalies which were found actually to lie along and parallel to this type of island-arc structure. The anomaly-trough does not always lie over the actual deep as a result of overthrusting of the island material in the deep so that the trough of the deep has its axis a little ahead of the axis of the crustal fold. The gravity-deficiency is postulated as a result of the light density of the material and of its having a great thickness in the axis of the corrugation. These same conditions appear to be present in the West Indies. As yet, only a portion of the island-arc has been examined but, as perfect agreement has been found so far, it is highly probable that the forthcoming Navy Gravity Expedition in this region will complete the picture as here suggested.

Another feature which offers much ground for speculation without possibility of present definite conclusion is the Bartlett Trough. This Trough extends from the south end of Cuba to

Honduras and is a marked oceanic "deep" that is significant from three standpoints: It is outlined by sharp cliff-like boundaries which are straight enough to suggest fault-escarpments: it is reflected by positive anomalies which would hardly be expected if it is a down-dropped block; and it lies in the line of en echelon structures that marks the zone of horizontal shear between the forward-moving massif postulated as responsible for the island-arc structure and the Cuban Block to the north. Hess [pp. 33-37 of 13] postulated that it was the result of horizontal movement along a zigzag fault. How such a condition would be reflected by positive anomalies invades the realms of speculation. Did more plastic, high-density material ooze into the ruptures resulting from these en echelon voids at depth to give the high positive anomaly observed over the Trough? Or what is the case? On the idea of a plastic, dense, underlying asthenosphere some such mechanism might be possible, but the proof of such a theory is going to be exceedingly difficult.

The main value of the West Indian Map (Fig. 4) lies in its indicating how the intricate structure of a region is revealed by gravity-anomalies where sufficient control is had. This is best exemplified in Cuba in the region around Colon. It also shows how theories such as those on the formation of island-arcs can be checked to a high degree of certainty by gravity-data.

Summary and conclusions

All of the maps presented are of a very preliminary nature, but it is believed that they are capable of serving to call attention to the main facts which are briefly:

(1) There does exist a definite relationship between gravity and geologic structure.
(2) In general, the gravity-profile represents the configuration of the crystalline basement.
(3) This relation is revealed by the relative value of the anomalies to each other rather than by the sign of the anomaly.
(4) The anomalies are determined almost entirely by the density and thickness of the material immediately adjacent to the station and underlying it.
(5) The basement-structure is masked by the presence of abnormal- or subnormal-density material overlying it.
(6) Where situations of this type exist, they can be detected by studying the general areal geology or by evidence of a geologic nature as revealed by well-logs.

In conclusion, it cannot be too highly stressed that other methods of geophysical research and exploration such as the magnetic, seismic, and torsion-balance methods bear similar relations to the geologic structure as does the pendulum-method of gravity-investigation here discussed, and all of these can be used as check-methods against each other in working out the geologic structure of a region.

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Washington, D. C.
May 1 and 2, 1936

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PROGRESS-REPORT ON A THREE-COMPONENT SEISMOMETER AND TILTMETER

L. B. Slichter

A recently completed 3-component portable seismometer and tiltmeter of compact design was shown and discussed. This instrument is one of a number which are being constructed for the observation of ground-motions from artificial explosions. Testing of the first model is now in progress. The instrument gives promise of being sufficiently sensitive and reliable for use at observatories, and for recording tilt-phenomena. In the design, special attention has been given to the matter of reducing thermal effects, and of maintaining stability of adjustment.

The following are the main data concerning these instruments: Period, about 2 seconds; damping, magnetic; pendulum-length, 13 cm; pendulum-mass, 2500 grams; static magnification, selectable in the range 80 to 25,000. Variation in static magnification is obtained by changing either the optical lever or the mechanical magnification-element or both. The mechanical magnification-element is a modification of Taylor's design. This, because of its symmetry, is theoretically balanced against thermal and elastic errors. Electrical calibration-coils are built into the instrument for the convenient determination of the dynamic constants and scale-factor. Electrical control of the zero-position of the light-spot is also provided. In the vertical component a Chatillon isoelastic spring of LaCostes' zero-length design is utilized.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

PROGRESS-REPORT ON THE RESEARCH CONNECTED WITH THE TIMISKAMING EARTHQUAKE OF NOVEMBER 1, 1935

Ernest A. Hodgson

The paper reported the details of the location of the epicenter of this earthquake by means of the arrival-times at seven seismological stations, most of which were within 400 miles of the epicenter. The field-work confirmed the location so deduced. Details of that work were given.

The location was based on the use of the graphs recently published by Brunner and assumed a focal depth of 200 km (125 miles). All the evidence from the field was in accord with this deduction.

Records of this earthquake were requested and have been coming in ever since. All available are now probably in hand and a study of them has been begun. They do not altogether support the assumed focal depth. The P-phases, etc., are not generally in evidence but most of the records show the large S-waves and small L-waves characteristic of deep-focus earthquakes. This phase of the subject is to be studied with care.

The writer proposes to fly over the epicentral area in the near future as soon as the ice is gone from the lakes. The gravel-banks bordering the many lakes were cracked at the time of the earthquake. The ice of winter will undoubtedly cause small landslides. It is proposed to see what the distribution of these may be.

It is hoped that a gravity-station will be established at Timiskaming and that three of the stations occupied previously about the area will again be visited.

Dominion Observatory,
Ottawa, Canada

CURRENT GEOPHYSICAL ACTIVITY IN TEXAS AND LOUISIANA

Donald C. Barton

(Abstract)

The geophysical activity in Texas and Louisiana at the present time is as follows: Seismograph crews in the Gulf Coast, 77; in east Texas, 13; in north Texas, west Texas, and southeast New Mexico, 6; total, 96. Torsion-balance crews in the Gulf Coast, 32; in east Texas, 1; in north

Texas and west Texas, 3; total, 36. Magnetometers, 7. Gravimeters, 7 (all in the Gulf Coast). Pendulum crews, 3 (all in the Gulf Coast). Experimental electric crews, 2. The grant total of all types of geophysical crews is 151.

Humble Oil and Refining Company,
Houston, Texas

PROGRESS-REPORT IN SEISMOLOGY FOR THE UNITED STATES COAST AND GEODETIC SURVEY

E. W. Eickelberg

The routine work of the Coast and Geodetic Survey in seismology was quite well established by the time of the last meeting and is outlined in the report of the Section of Seismology (pp. 96-99, Transactions of 1935). Only changes and additions in this part of the work will be mentioned. The same abbreviations will be used as in that report: MIT for Massachusetts Institute of Technology; CGS for Coast and Geodetic Survey; JSA for Jesuit Seismological Association; CIW for Carnegie Institution of Washington; Cal-Tech for California Institute of Technology; SRL for Seismological Research Laboratory; UC for University of California; NBS for National Bureau of Standards.

Earthquake information--There has been little change. Special mention should be made of the work of W. E. Maughan, Assistant Meteorologist in charge of Weather Bureau Office at Helena, Montana, who kept the record of the more than 1800 shocks that have occurred in the series that began October 3, 1935, and is still in progress (93 shocks during March). He also cooperated by looking out for the strong-motion instrument left at Helena by request when the CGS personnel was obliged to return to duty in California. In California the number of reports has fallen off somewhat more than the earthquake-activity. This is in part due to the lack of adequate personnel to take care of data when obtained. Plans are being worked out between CGS and UC to improve this situation. There is ample opportunity for addition to the service for the country as a whole.

Teleseismic work--The following additions have been made during the year. The station at College, Alaska, was put into operation November 15, 1936. Professor E. H. Bramhall of the University of Alaska is supervising its operation, in addition to having made the installation. A station at Butte, Montana, was made possible by loan of one component of a Wood-Anderson instrument by Dr. Day, Chairman of the Advisory Committee in Seismology of the CIW, and of recorder and other accessories by CGS, the site and installation and servicing being by the Montana School of Mines. The Jamaica Station has been equipped with a Wood-Anderson seismometer, loaned by the CIW, and with a recorder loaned by Georgetown University.

Immediate location of epicenter was carried out for 23 earthquakes. There have been no changes in the plan for immediate determination of epicenters except that St. Louis now informs Science Service as to probable accuracy of their determination of epicenter.

Recording of strong earth-motion and related activity--The important feature of the year's strong-motion work was the emergency installation of an accelerograph at Helena, Montana, October 21, 1935, which resulted in a large number of strong-motion records. Some of these were complete, that is, the recorder was in operation when the earthquake occurred so that no part of the record was lost through delay in action of starter. The activity was moderate in the California Region and only eight strong-motion records were obtained of five earthquakes.

The program of measuring the vibration-periods of buildings, tanks, bridges, dams, and of the ground was greatly curtailed during the year as funds became exhausted and this part of the work is now largely cooperative, especially with Stanford University, and is applied to special problems. Fortunately, it has been possible to publish most of the results of the special work in this field and this will soon be available.

Records of interest during the past year--The most interesting records of the year were those obtained of the series of Montana earthquakes. Though the series started on October 3, 1935, and there was a destructive earthquake October 18, the instrument was not installed until October 21. The most important of the records obtained were those of the destructive earthquake of October 31 and strong aftershocks of November 28, 1935, and February 23, 1936. There were a number of records obtained while the recorder was in operation so that the entire shock was recorded. It has been definitely demonstrated by actual records that earth-movements are different for every earthquake, which makes necessary indefinite continuation of the obtaining of records.

Instrumental developments--The records of the Montana earthquakes were vastly superior to those of the Long Beach, California, earthquake of 1933 and this is due to the continuous improvements of instruments since that time. In the case of Montana it was necessary to improvise a starting device responding to vertical motion and this has since been improved. Plans have been worked out for setting up an accelerograph in open country as, for example, in the case of an earthquake in an unsettled region such as the Nevada earthquake of December 20, 1932.

Work on shaking table at National Bureau of Standards for tests of high-magnification seismographs was completed and the platform has been dismantled. The results were in part presented by Dr. Frank Wenner of NBS and H. E. McComb of CGS before the Philosophical Society of Washington, but they have not yet been published.

Crustal movements--Plans have been made for precise levels in the vicinity of Helena, Montana, a party being in the field at the present time.

Work has been done in California as follows: The Merritt tiltmeter has been in operation at UC. With the aid of a grant from the National Research Council, Mr. Merritt has developed a recording device which gives hourly records and this has been given a thorough test. There have been no earthquakes on the Hayward Fault during the period and there have been no tiltmeter records such as have been found in Japan to be characteristic of earthquakes.

Utilization of results--Strong-motion records have been in demand as well as their interpretation, especially the derivation of displacement-curves from accelerograms by the double-integration method developed by Mr. Neumann of CGS. These records have been used by Mr. Ruge of MIT to operate a shaking table on which are tested models of tanks and other structures, the motion of the ground during the earthquake being impressed upon the platform by a photoelectric method. There has been demand for information from those responsible for the construction of great dams and bridges as well as other structures.

Publications--"United States earthquakes for 1933," which was issued during the year, was the first issue of this series to contain strong-motion results, one-half of the number being devoted to this class of work. "Earthquake investigations in California, 1934-1935" is a special publication now in press and almost ready for distribution, describing the work of the various parties of the CGS engaged in seismological investigations, and containing a large amount of vibration-data of special interest to engineers.

Mimeographed reports issued during the year included periodic progress-reports on the California work, quarterly reports on non-instrumental results for the Pacific Coast Region, monthly instrumental reports on teleseismic work, and preliminary epicenter-results.

The following is a list of the seismograph-stations of the United States. Those stations marked with a plus (+) sign have, during the past year, sent immediate information for the determination of preliminary epicenters in cooperation with Science Service.

Seismograph-stations of the United States

Location	Supporting organization	Symbol on map as
Alabama		
Silver Hill (near Mobile)	Silver Hill College	Jesuit
Arizona		
+Tucson	Tucson Magnetic Observatory, CGS	Coast and Geodetic Survey
Arkansas		
Little Rock	Little Rock College	Jesuit
California		
+Berkeley	UC	Independent
Ferndale	J. Bognuda, cooperating with UC	Independent
+La Jolla	SRL	Independent
Mineral	Lassen Volcano Observatory, U. S. Geological Survey	Independent
Mt. Hamilton	Lick Observatory Seismological Station, UC	Independent
+Mt. Wilson	CIW	Independent
Palo Alto	Stanford University and UC	Independent
+Pasadena	SRL	Independent
Point Loma	Theosophical University	Inactive
+Riverside	CIW-City of Riverside	Independent

Seismograph-stations of the United States--Continued

Location	Supporting organization	Symbol on map as
California--Concluded		
Santa Barbara	CIW-Santa Barbara Museum of Natural History	Independent
Santa Clara	Santa Clara University	Jesuit
San Francisco	California Academy of Science	Independent
+Ukiah	CGS	Coast and Geodetic Survey
+Tinemaha	SRL	Independent
+Haiwee	CIW	Independent
Colorado		
Denver	Regis College and JSA	Jesuit
Connecticut		
New Haven	Yale University	Inactive
District of Columbia		
+Georgetown	Georgetown University	Jesuit
Illinois		
Chicago	Loyola University	Jesuit
+Chicago	CGS-U. S. Weather Bureau	Coast and Geodetic Survey
Iowa		
+Des Moines	Seeburger Seismograph-Station	Independent
Kansas		
Lawrence	University of Kansas	Proposed
Louisiana		
New Orleans	Loyola University	Jesuit
Maine		
+Technology	MIT	Independent
Maryland		
Woodstock	Woodstock College	Jesuit
Massachusetts		
+Cambridge (Oak Ridge)	Harvard University	Independent
Weston	Weston College	Jesuit
Worcester	Holy Cross College	Jesuit
Williamstown	Williams College	Independent
Michigan		
+Ann Arbor	University of Michigan	Independent
Missouri		
Florissant	St. Louis University	Jesuit
+St. Louis	St. Louis University	Jesuit
Montana		
+Bozeman	Montana State College and CGS	Coast and Geodetic Survey
Butte	Montana School of Mines, CIW, and CGS	Independent
Nevada		
Reno	University of Nevada	Independent
New York		
Albany	University of State of New York	Inactive
+Buffalo	Canisius College	Jesuit
+Ithaca	Cornell University	Independent
+New York	Fordham University	Jesuit
New York	Museum of Natural History	Independent
Ohio		
+Cincinnati	St. Xavier College	Jesuit
Cleveland	John Carroll University	Jesuit
Pennsylvania		
+Pittsburgh	University of Pittsburgh	Independent
+Philadelphia	Franklin Institute	Independent
+State College	Pennsylvania State College	Independent
Swarthmore	Swarthmore College	Inactive
South Carolina		
Columbia	University of South Carolina-CGS	Coast and Geodetic Survey
Texas		
Denton	John W. Crain	Independent
Utah		
Salt Lake City	University of Utah	Independent
Vermont		
+Burlington	University of Vermont	Independent

Seismograph-stations of the United States--Concluded

Location	Supporting organization	Symbol on map as
Virginia		
+Charlottesville	University of Virginia	Independent
Washington		
Seattle	University of Washington	Independent
Spokane	Gonzaga University	Jesuit
Wisconsin		
Milwaukee	Marquette University	Jesuit
+Madison	University of Wisconsin	Independent
Nebraska		
Lincoln	Nebraska Wesleyan University	Proposed

In addition to those stations marked with a plus sign in the above list there are a number of stations outside the United States which have cooperated in sending immediate information for the determination of preliminary epicenters. These are listed below:

Manila Observatory, Manila, Philippine Islands
Dominion Meteorological Observatory, Victoria, British Columbia, Canada
Royal Observatory, Hongkong, China (via Manila)
l'Observatoire de Zi-Ka-Wei, Zi-Ka-Wei, China (via Manila)
University of Hawaii, Honolulu, Territory of Hawaii
Magnetic Observatory, CGS, Sitka, Alaska
Magnetic Observatory, CGS, San Juan, Puerto Rico
University of Alaska, College (near Fairbanks), Alaska
Observatorio del Ebro, Tortosa, Spain (through St. Louis University, St. Louis, Mo.)
The Observatory, Apia, Samoa
Huancayo Magnetic Observatory, CIW, Huancayo, Peru
The Dominion Observatory, Ottawa, Canada

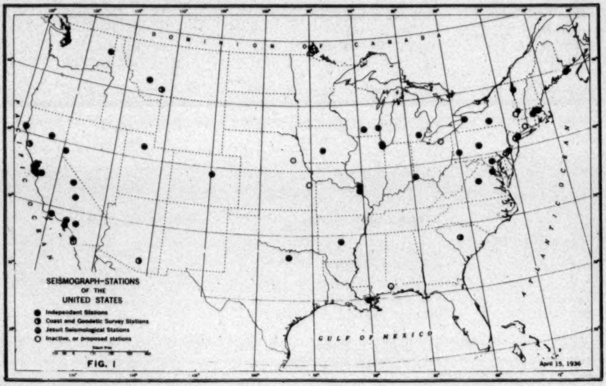
DOMINION OF CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
SEISMOGRAPH-STATIONS OF THE UNITED STATES
● Independent Stations
● Coast and Geodetic Survey Stations
● Jesuit Seismological Stations
○ Inactive, or proposed stations
April 15, 1936

FIG. 1

U. S. Coast and Geodetic Survey,
Washington, D. C.

GEOLOGICAL IMPLICATIONS OF DEEP-FOCUS EARTHQUAKES

V. C. Stechschulte

Five years ago at the Pasadena meeting of the Seismological Society the writer ventured to state in a preliminary report of the evidence for a focal depth of 400 km for the Japanese earthquake of March 29, 1928, that the occurrence of earthquakes at a depth of 400 km may well have large significance for isostasy and related problems, as well as in regard to structure, constitution, and condition of the Earth. At that time deep foci enjoyed only a modicum of scientific respectability, but since then they seem to have found an accepted place in the family of scientific data, and interest has arisen in regard to their significance and implications. The present paper is an attempt to develop, to a little extent, some of these implications.

Probably the main difficulty against accepting the reality of deep foci lay in the fact that our picture of "ordinary" earthquakes was that of a sudden release from accumulated elastic shear, the classical example being the California earthquake of 1906. But how can you have shear at great depths? It is difficult enough to imagine shear at 50 km or even at 30 km, but it may be questioned whether it is essentially more difficult to picture it at 500 km than at 50 km. The difficulty varies in degree, not in kind. The big stumbling-block is, of course, that accepted speculation has led us to think of the rocks having zero-strength at great depths on account of the excessive temperatures presumably existing there. Here, then, we have the first and probably the most important implication of plutonic earthquakes, namely, strength at unexpected depths. However, before such a conclusion is accepted it will naturally be desired that other possibilities be eliminated. Are such shocks not due perhaps to an explosive activity of some sort? It would seem just as difficult to imagine anything akin to a gas- or dynamite-explosion taking place on the necessary large scale as to imagine shear. However, appeal must be made not to the imagination, but to the seismographic records. Here various lines of evidence present themselves.

First, from the direction of the initial movement. If the source were an "explosion," one might well expect the direction of motion of the first impulse to be generally the same, probably a compression. However, no such consistency appears. Thus of 219 shocks during the course of four years qualified in the Bulletin of the Seismological Laboratory at Pasadena as "deep," either with assurance or questionably, 127 showed the first motion as a compression and 92 as a dilation. The question has been raised in a letter to the writer whether substances might not change their state, with release of energy, but sometimes with an increase and sometimes with a decrease in volume, provided their stable conditions for temperature and pressure have been passed without change having occurred. I do not know whether such an event is to be expected or not. I should be inclined to think, however, that the changes taking place in the depths would probably be more unidirectional in character than the above-quoted figures would indicate if the suggested hypothesis were true. However, neither for a given earthquake do we find uniformity of motion at various stations, but rather compressions and dilatations scattered as we find them in the case of near-surface shocks. Kawasumi and Yosiyama (Proc. Imper. Acad., v. 6, pp. 345-348, 1934) have even gone so far as to assign, on the basis of the distribution of first motion, a definite dip and strike for the plane along which the quake of February 20, 1931, took place, whose depth, according to the study by Scrase, was about 360 km. Still, it should be said, they do not speak clearly of a fault along that plane. But whether one is prepared to accept this result or not, it would seem that the balance of evidence from the first motion tends to be against a purely explosive source.

More positive evidence of shear at the source and therefore of strength in the material is to be found in the abundance and apparent predominance of the energy carried by the shear-waves on the seismograms. Indeed, the sharpness and intensity of the onset of the transverse waves has been noted as characteristic of seismograms of deep-seated shocks. Presumably such great prominence of shear-waves connotes a shear at the source and therefore strength. But how great is this strength? The analogy of pitch fractured by a "hammer-blow" may be recalled. However, one finds difficulty in thinking of a process taking place suddenly on a large enough scale to deliver the "hammer-blow" to the depths of the Earth to give us some of the energetic deep shocks that have been recorded, and if a large enough "hammer-blow" were given, this could only be by an "explosion," and then the argument from the distribution of first motion would apply. Again, if some time is required for such volume-changes, or whatever they are, to take place on a large enough scale, it would seem that the material must have some degree of strength, and probably a fairly high degree, in order to store even for a comparatively short time the large amount of shear-energy indicated by the seismograms. As further evidence of the abundance of shear-energy at the source, one may add that ScS, the shear-wave reflected from the central core, is frequently seen recorded with rather astonishingly great amplitudes.

If now we may conclude, albeit cautiously, from the character of the seismograms of deep-focus or plutonic earthquakes to shear at depth and from shear to notable strength at depths down to 600 km and more, then at least this much would seem to follow in regard to isostasy, that we cannot have a universal and uniform level of compensation, or, at any rate, that such level cannot be at the comparatively shallow depths which have been assigned. I have said "universal" because we do not know enough as yet about the geographical distribution of deep foci. Wadati tells us of a distribution along linear zones for the deep foci near Japan. Whether something similar may show up for other regions remains to be seen. But whatever the zonal distribution, the deep shocks seem to point to deep-seated spherical inhomogeneity in the Earth, whether it be in material or thermal condition, or state of aggregation. Again, if strength at great depths be admitted, it would seem that isostatic compensation can hardly be purely local in character--at least not universally so. On the other hand, the evidence from deep earthquakes does not allow us immediately to conclude that the crust, at all parts of the globe, has large strength down to great depths.

In connection with the possible zonal distribution of deep foci, it may be recalled that, even in the small percentage of the Earth's surface that has been gravitationally surveyed, there are also zones where isostasy does not represent the facts. The question may be raised whether the long narrow strips of great negative anomalies passing over into areas of large positive anomalies discovered by Vening Meinesz in the East Indies do not indicate, as Jeffreys points out, "a strength comparable with that of the upper layers through a depth of at any rate some hundreds of kilometers." What seems to be the deepest earthquake of which we thus far have record, that of June 29, 1934, with a focal depth of about 675 km, took place, according to the epicenter adopted by the writer, in the Flores Sea in the East Indies, but in a region where Vening Meinesz indicates positive anomalies. I have recently plotted the epicenters for the last eight years as given in the International Seismological Summary, and compared them with the anomaly map given by Vening Meinesz. The epicenters do not lie for the most part along the narrow zones of great negative anomalies, but rather in the positive areas. This is certainly true, except perhaps at the westernmost end, for the elongated zones parallel to the Sumatra-Java Arc, probably less so for the zone trending north toward Mindanao. One might perhaps surmise that the deep shock mentioned above and others of shallower depth are a response to the great difference in load represented by the anomaly-gradient. Vening Meinesz, on the other hand, considers earthquakes and the disturbances of gravity as due to tectonic activity, and has elaborated his buckling hypothesis to explain the great anomalies. One might venture, however, in the light of what has been said, to question the universal validity of the principle of interpretation stated by him (Gravity-expeditions at sea, v. 2, p. 18): "We can, however, express an important rule for guiding our interpretations if we assume that the anomalous masses are only occurring in the upper layers of the Earth. This assumption is obviously probable because all our geophysical considerations converge towards the assumption that the plasticity of the materials increases when we get deeper into the Earth. So deviations will be more and more unlikely for deeper layers." On the other hand, probably many will not be ready to agree with a statement recently made in a letter to the writer: "If the deep material can build up big enough stresses to generate a first-class earthquake, it is beginning to look as if we should be trying to invent a new explanation of isostasy."

Again, if there be notable strength at great depths, and if we are to retain our traditional view that high temperature tends to destroy strength, then one feels moved to agree with De Lury (J. Geol., v. 41, pp. 748-756, 1933) in asserting that it is incorrect to project an average gradient of 30° per km linearly into the Earth, that the lowest observed gradient might perhaps be the most proper one to project, and that, in any event, there may well be very deep-seated distortions of the geoisotherms. Hence another implication of plutonic earthquakes would be in regard to the thermal condition of the Earth's interior, as also in regard to theories of convection-currents within the Earth.

In line with the above, the following paragraph from Jeffreys' book, "Earthquakes and mountains," may be quoted (pp. 164-165): "We do not know enough about the variation of radioactivity to produce a theory capable of detailed comparison with observation, but we can obtain suggestive results in general terms. We should expect, for instance, that at depths down to 600 km or so, the cooling since the Earth solidified has been considerably more below the oceans than below the continents. This is verified by the distribution of mountains around the Pacific. We have a practically continuous chain or series of chains along the western coasts of North and South America. This would be expected if the ocean-floor is the stronger, because when contraction led to yield the strength would be reached first in the weaker place, and the continental rocks would be crumpled along the ocean-margin." Perhaps bearing on the truth of the above surmise is the interesting fact that the deep-focus earthquakes from South America occur well under the continent, and among these shocks are some of the very deepest of which we have record.

Either one assumes, on account of deep-focus earthquakes occurring there, greater strength under the continents than under the oceans, and then Jeffreys' explanation would be weakened, or else there is strength at even greater depths under the ocean than the depths indicated by the subcontinental deep foci. On the other hand, many deep earthquakes occur in oceanic regions, so that the evidence is inconclusive.

One more point may be added. If there be sufficient strength at depths of 500 or 600 or even 700 km to allow the storage of shear-energy, then we must also conclude that there will still be appreciable strength well beyond those depths, for it is hardly to be expected that the shear would take place where strength has practically disappeared.

Much remains to be known still about deep-seated earthquakes, their relative frequency, their geographical distribution, whether certain depths are preferred in certain localities, what relation, if any, exists between deep foci and volcanic zones, etc. However, it is believed that the evidence already available is at least sufficient to justify the title of this paper, Geological implications of deep-focus earthquakes.

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PROGRESS IN ENGINEERING-SEISMOLOGY RESEARCH AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Arthur C. Ruge

(Abstract)

The recent research at Technology has been concentrated largely upon three important problems, none of which would offhand seem to be very difficult, but which have already consumed over two years of work and the end is not yet in sight. These are (1) the behavior of elevated water-tanks when subjected to earthquake-motions, (2) the development of a quake-resistant design for such structures, (3) the development of a machine for reproducing actual earthquake-motions.

The first problem was begun by the model-method, using simple harmonic motion for simulating the motion of an earthquake. While some valuable results were obtained in this way, it was all too apparent that such data, however, precise, are still not truly quantitative because earthquakes are not simple harmonic in character.

The results of these studies did, however, suggest a radically different type of antiseismic design for elevated tank-structures and some simple harmonic-motion studies were made on a model embodying the new principle. Briefly, the new design is provided with a wide range of safe deflection and also with damping action to kill building-up effects. At the same time, the structure is quite rigid against ordinary wind-force. Unfortunately, the new design is highly non-linear and, beyond a few preliminary simple harmonic-motion tests, it was considered idle to go farther with such crude approximations of earthquake-motions.

Accordingly, the next step was to design and build a machine for reproducing the actual irregular motion of earthquakes. A study was made of many possible schemes before the new machine was designed, and the advantages and drawbacks of each were carefully weighed. The new earthquake-machine at Massachusetts Institute of Technology is still in its infancy. In fact, as soon as it was considered satisfactory for the purpose, it was immediately put to work on a continuation of the model-studies of elevated water-tanks. It is estimated that there are several more months of development-work to be done on the machine before it can be said to have reached its full efficiency.

Studies of the behavior of elevated water-tanks when subjected to actual earthquake motion as recorded March 10, 1933, in Los Angeles, showed that the new design has a factor of safety of at least two over the standard structure (reinforced for a ten per cent gravity side-loading). The indications are that present design-methods are not adequate and do not rest upon a rational basis.

Although there is a need for an extended study of the new design, the most important question now to be answered is economic. So far as the tank-structures themselves are concerned, it probably would not pay in the long run to make provisions against earthquakes. It is only when the elevated water-supply forms a vital part of a fire-protection system, or when it protects the health of the community, that it is worth spending a considerable amount of money reinforc-

ing the tower. How much expenditure is justified is a question now being considered by the underwriters of fire and earthquake insurance and by other interested parties. The engineering problem is already fairly well solved.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

IMPROVEMENTS IN STRONG-MOTION SEISMOGRAPHIC EQUIPMENT

R. E. Gebhardt

In 1931 the United States Coast and Geodetic Survey began an extensive program of investigation of strong seismic motions. The program has been carried on continuously since that time, and as a result of a vast amount of field-work and the accumulation of records a number of changes have been made for the purpose of improving the performance of the instruments. Other changes have been made necessary because of the more exacting requirements of the staff at the office concerned with the reduction of the records.

Of the changes made during the past year, the most important one has been the installation of double-magnification vanes on the twelve-inch accelerographs. These vanes have been installed in order to guard against loss of record during a strong shock and to aid in the interpretation of the grams. The original mirror was not disturbed but a second one was placed on the axis of rotation of the vane. The angle of inclination of the second mirror being variable makes it possible to adjust the lower magnification over a fairly wide range. For normal use this mirror is set so that its magnification is approximately one-seventh that of the regular mirror. The

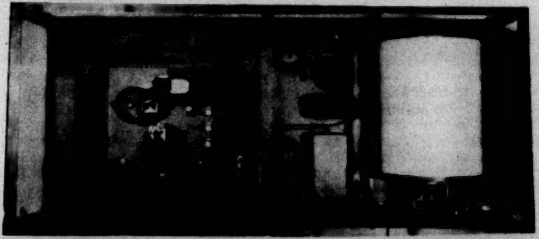

FIG. 1—BASE-LINE-MIRROR HOLDERS MOUNTED ON BASE-PLATE OF 12-INCH ACCELEROGRAPH

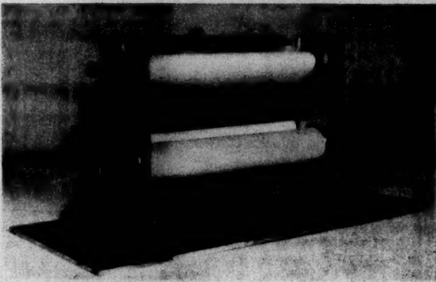

FIG. 2—RECORDER USED ON MONTANA ACCELEROGRAPHS

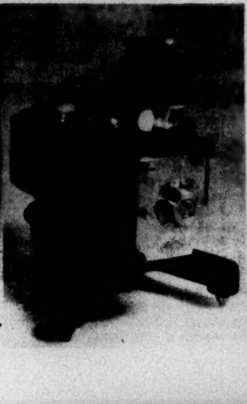

FIG. 3—ACCELEROMETER DESIGNED FOR THE MONTANA ACCELEROGRAPHS WITH SLIDING MAGNETIC-SHUNT, DOUBLE-MAGNIFICATION VANE, AND BASE-LINE-MIRROR MOUNTED ON ACCELEROMETER-BRACKET

two light-beams are brought out at the same height by the use of a small right-angle prism, thus eliminating parallax between the two spots.

A second improvement has been the installation of a sliding magnetic shunt, operating on a rack-and-pinion arrangement, which varies the damping ratio over a range from 5:1 to about 30:1. The damping of course depends largely on the strength of the cobalt-steel magnet but these magnets can be adjusted approximately to the same value.

The third important improvement has been the addition of a base-line to the record to facilitate the interpretation. The base-line serves as a reference-line to eliminate any relative motion of the drum and the accelerometer-bracket that might be caused by warping or torsional strains in the base-plate of the instrument. The only way these mirrors could be installed on the instruments already in operation was to place them along the front edge of the base-plate, slightly lower than the accelerometer-mirrors. This causes a little parallax between the two spots; while this feature is not desirable, it is not serious (see Fig. 1).

During the past few months, interest in the Montana Region has been responsible for the construction of several accelerographs in the Instrument Division of the United States Coast and Geodetic Survey. As these instruments are now under construction, it was possible to incorporate several changes and improvements that are not possible on the instruments in operation. A new-style tape-device has been developed to accommodate a paper tape 12 inches wide, and up to 400 inches long. The preliminary tests with this recorder have been very satisfactory, showing no uneven motion of the paper (see Fig. 2).

The base-line mirror has been changed to the bracket of each accelerometer. This completely eliminates the parallax that was present with the first mirrors described above. The new installation is adjustable in azimuth and in inclination, and is so constructed that the mirror may be diaphragmed readily (see Fig. 3).

Another addition to these accelerographs is a starter to respond to vertical impulses. The steady mass will pivot about a single flat spring and the mass (about one-half pound) will be balanced by a vertical spring.

In closing it should be stated that everything possible is being done to improve the quality of the records obtained from the strong-motion instruments.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SAND-CRATERS AND THEIR POSSIBLE SIGNIFICANCE

P. O. Macqueen

1. It is the purpose of this paper to explain the laboratory-method in which "sand-craters" are made to occur and to point out some of the possible conclusions which may be drawn from this relatively simple experiment. N. H. Heck, Chief of the Division of Terrestrial Magnetism, United States Coast and Geodetic Survey, has joined with me in this discussion and has advised me of several important comparisons. Perhaps, however, the subject has already been published and the fact will be quickly brought to our attention. In any event we have not seen it in print and we wish at this time to submit it to criticism in order to bring out the true conclusions, if possible.

2. "Sand-craters" or sand-rings, as they might be called, are observed under certain conditions in nature where an upward jet of water passes through a bed of submerged sand such as might occur on a very small scale in the case of a spring with a fine, clear sandy bottom. In this case the action of the vertical water-currents through the sand cause small craters or rings of sand to form on the bottom of the spring and these rings have the appearance of minute flat volcanic craters. Due to the fact, however, that the surface is submerged, the sand ejected by the jet is conveyed a short distance away from the center of jet and deposited in a ring or circle around the center of the disturbance. These rings, however, have a flat saucer-like shape and are decidedly different from the normal volcanic crater-shape as explained later.

3. My first experience with sand-craters was in connection with the large slow sand water-filtration plant for Washington, D. C. I was in charge of this plant at the time and was engaged one day in the inspection of one of the filters which had just been cleaned and which was

being put back into service. The customary method of doing this is to first allow the water from the filtered-water reservoir to reverse its flow up through the clean sand until a depth of several inches above the sand is obtained. The water in this particular filter was just in the process of bubbling up through the sand in many places and I was astonished to see that each little water-bubble in the sand was in the center of a small shallow crater about four inches in diameter and one inch deep. These sand-craters were obviously the result of the upward flow of water through the sand. The most interesting thing about these formations to me at the time was that each crater was a perfect circle and that the circumferential ridges were of uniform height. I watched them form for some time and then decided to make some laboratory-experiments with these sand-craters.

4. The laboratory-method of performing this experiment is very simple. A watertight box of any convenient size such as three feet square and three feet deep is first obtained and filled to within about four inches of the top with fine clean sand. Next a water-jet consisting of a small bent pipe is embedded in the sand in the center of the box with the orifice of the pipe about six inches below the sand surface. This pipe is connected to the water-supply with a small hand-valve near the box so that the flow of water may be easily varied. A waste pipe should also be provided on one of the upper edges of the box so as to provide for a suitable overflow. The box may now be filled with water to a depth of several inches above the sand which should be smooth and level and the experiment may be started. General arrangements are shown in Figure 1.

5. By opening the valve slowly a small amount of water is allowed to flow up through the sand from the pipe-orifice and the ejected sand immediately forms a small circle around the center of water-disturbance. This sand-circle soon builds up to a height of about one inch and the diameter and height of the circle become fixed for the flow of water used. With a little experimental work "sand-craters" of various diameters and heights can easily be formed. The dimensions of the "sand-craters" are changed by the velocity of flow, the depth of water above the sand, and the depth of the pipe-orifice below the sand. The larger circles occur as may be expected with the higher velocities. It is interesting to observe the suddenness with which the craters occur, the perfect shape of the rings, and the sharpness of the circular edges. Figures 2 and 3 from photographs which were taken by James McQueen, Civil Engineer, show the general shape of the "sand-craters." Secondary rings of sand occur outside of the principal ring as shown in Figure 2, but these are always much smaller than the principal ring.

6. The explanation for these phenomena is simple and obviously it is the result of the circular wave-action radiating out from the water-bubble. The water-jet pushes the fine sand up from the center and the circular wave deposits the sand at a uniform distance from the center of disturbance. The exact mechanics of these rings involving the peculiar sharp-crested shape of the circular edges is much more complicated. The secondary rings are hidden by the principal ring and remain much lower in height. The laboratory-experiments are made with small "sand-

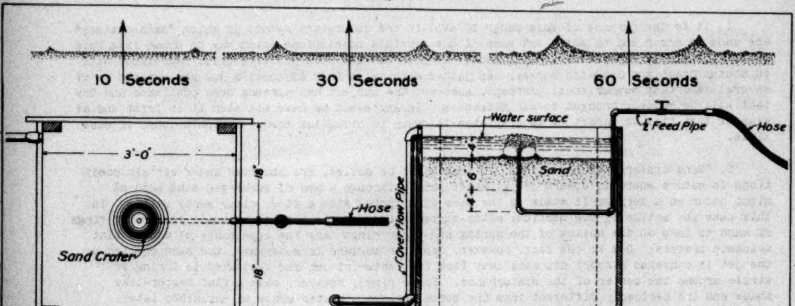

FIG. 1—SKETCHES OF SAND-CRATER APPARATUS AND SAND-CRATERS

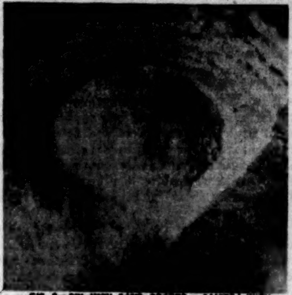

FIG. 2—SIX-INCH SAND-CRATER—CAMERA WITH 45°-ANGLE EXPOSURE

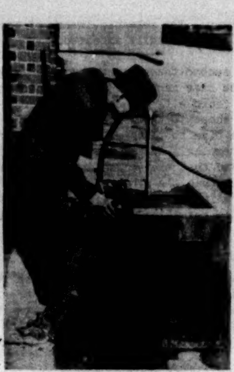

FIG. 3—EXPERIMENTAL APPARATUS FOR SAND-CRATERS

craters" of from six to twelve inches in diameter but it is readily possible to assume that "sand-craters" of from six to twelve feet in diameter would be formed by much larger water-jets and thicker sand-deposits. Using the ratios of sand- and water-depths as determined by the small-scale experiments we may assume in a general way that a "sand-crater" as much as twelve feet in diameter would be formed with water about two feet deep, sand about four feet deep, and a large subsurface jet of water at least six inches in diameter. It would be very interesting to perform the sand-crater experiments on a large scale and determine whether it would be feasible to obtain large craters such as this in the laboratory.

7. The step from the small 12-inch diameter "sand-craters" to the large 12-foot diameter "sand-craters" is one which is relatively easy for our imagination to take but the question which follows next is far less obvious and one which involves considerable doubt. We may ask naturally if it would be possible for a condition to occur in nature which would cause a crater of sand or other material as great as 1000 feet or even many miles in diameter but it is hardly possible to assume the conditions on the Earth under which they would occur without resource to volcanic eruptions in which the disturbance would be caused by jets of hot water, gas, steam, or lava. The most important significance of these small laboratory-model "sand-craters" is their striking similarity to the volcanic craters on the surface of the moon and this comparison will be discussed first. Thousands of clear-cut photographs of the moon-craters are easily available and a few are pictured in Figure 4 for comparison. The main features of this striking similarity of the moon-craters to these small laboratory "sand-craters" are the true circular shapes of the crater rings, the flat saucer-like shape of the craters, the uniform height and sharpness of the crater-rims, and their equal elevation above the inside and outside of the crater.

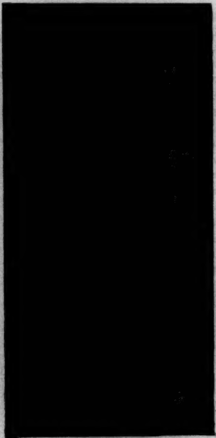

FIG. 4—THE LUNAR APENNINES AND CRATERS

8. Astronomers have noted the peculiar shape of the moon-craters for many years but even at this time they are not in agreement as to exactly how they were formed in the past ages. Various theories have been presented but none have been universally accepted. One of the theories frequently expressed is that the surface of the moon was bombarded with thousands of meteors while the surface was still partly plastic and that the craters were caused by this bombardment. This theory is open to many criticisms, the main one being that such a bombardment could not by any possible means cause the true circular-shape craters which we can readily see with the telescope. Another criticism to this theory is that the Earth itself would have been subjected to this same meteoric bombardment and we have evidence that this

did not occur. The meteoric theory of the origin of lunar craters is not considered as being one which can be readily accepted.

9. A second theory of the manner in which the moon-craters were formed is that they occurred in much the same manner as the volcanic craters are now occurring on this Earth. Here again this theory is faced with the sharpest of criticism as the moon-craters are in general entirely different in shape to the volcanic craters on the Earth. The lunar craters are flat saucer-shaped rings from five to fifty miles in diameter with uniform rims whereas the typical earth-crater is a deep irregularly shaped depression at the top of high cone-shaped mountain. This difference is so marked that the second theory of the formation of the moon-craters is not generally accepted any more than the first one mentioned. Small sand-models of the formation of volcanic earth-craters are frequently made in laboratories by blowing a current of air up through dry loose sand and the resulting cone-shaped craters are quite similar to the typical volcanic craters on the Earth, such as Vesuvius or Fujiyama.

10. The third theory given for the origin of lunar craters is that they were caused by the bubbling up of gas to the surface of the moon while it was still in a partly plastic state. These immense bubbles were assumed to break and the central portion to fall back leaving a ring of material. This process may have been repeated many times resulting eventually in immense circular-shaped craters. The lunar plains or seas were then assumed to be caused by molten lava escaping from volcanic jets.

11. The fourth theory is that the lunar craters may have been formed by emission of molten lava from vents in the moon's crust, due to the tidal force of the Earth on subsurface lava-pockets on the moon. This molten material may have been alternately pulled out and then drawn back by the tidal forces and it is possible that rings of material may have been left after each period of lava-emission. These rings may have been gradually built up by these pulsating lava-emissions with the large circular craters as the final result.

12. Each of these theories has been discussed many times by astronomers but there has not as yet been any agreement as to which theory is the most logical. The striking similarity of the small laboratory "sand-craters" described in this paper to the lunar craters has been mentioned and it is possible to develop a new theory of the origin of lunar craters on the basis of this comparison. In order to attempt this comparison it is necessary to review present conditions on the moon's surface and draw a picture if possible of another way in which these thousands of circular moon-craters could have been formed.

13. In its present condition the moon is known to be an entirely dead planet without air, vegetation, water, ice, or internal heat, and its surface is generally assumed to be a loose, porous lava-formation. There are no winds or air-currents and the all-moon craters and other formations retain their sharpness of outline indefinitely. The force of gravity is only about one-sixth as strong as here on the Earth, and the effect of forces on the moon would therefore be far greater. In the past ages the moon was intensely hot and gradually cooled off so that we may assume that at one time its surface was covered with molten lava. This surface layer may have cooled off first to a great depth and the steam and other gases may have condensed and changed to a fluid to a depth of many thousand feet, leaving the center of the moon still intensely hot. Contraction and still further cooling of the moon's surface would cause volcanic emissions of gas or lava below the surface of the fluid and these eruptions may have caused the thousands of circular craters on the moon's surface in very much the same manner that the small laboratory "sand-craters" were formed. The striking similarity of the saucer-shaped model sand-craters with the present moon-craters has been mentioned. Instead of sand, however, the material in the case of lunar craters would be large and small pieces of lava which would become solidified after emission from the central jet. Due to the difference of gravitational force on the moon and the relatively high transporting power of a fluid which varies from the third to the sixth power of the velocity it is possible that this ejected material would be carried to a great distance from the center of disturbance and deposited under the surface of the fluid in a ring from five to fifty miles in diameter depending upon the force of the central jet.

14. To continue the picture, however, we must explain, if possible, the disappearance of the fluid from the moon's surface and we will have to assume that it was gradually lost into space due to weakness of the moon's gravitational force or that with the ultimate cooling of the moon it was gradually absorbed into enormous voids in the moon's center. It is possible, of course, to draw other mental pictures of the formation of these moon-craters by assuming eruptions through very thin molten lava as the fluid-cover but the one presented appears to be the easiest to visualize.

15. As a possible important point of significance of the experimental laboratory "sand-craters" the conclusion is here offered that lunar craters may have been originally formed by submarine volcanic action and that they possibly occurred in the manner described in the preceding paragraphs.

16. To come back to the Earth again, however, the question is raised as to whether the model "sand-craters" have any significance as far as earth-formations are concerned. Some study has been given to this question and with one possible exception there do not appear to be any large-scale earth-formations which have a definite resemblance to the model "sand-craters." Volcanic formations on the Earth are the result of eruptions of lava or cinders in free air and the cones are hence entirely different. Some few earth-craters such as Mauna Loa and Crater Lake have approximately circular shapes but they fall far short of being like the clear-cut, saucer-shaped laboratory "sand-craters." Earthquake-emission of mud and sand have been observed but these also fail decidedly to resemble the "sand-crater" models. The well-known large meteor-crater in Arizona, which has been described in detail by Dr. Clyde Fisher, is different in origin entirely.

17. The single known possible exception mentioned above is the very interesting formation known as the Carolina "Bays" which have been described by F. A. Melton and William Shriever in the Journal of Geology in 1933. The authors give complete descriptions of these large rings or bays near the coast of South Carolina which are from half a mile to a mile in diameter and suggest as the most logical hypothesis of origin that they are the result of meteorite scars. The semi-elliptical shape of the craters and other facts seem to make this hypothesis a very logical explanation.

18. It is possible, however, to visualize a manner in which these Carolina "Bays" could have been formed in practically the same manner that the small laboratory "sand-craters" were formed and to do this we again attempt to build up a series of conditions which might lead to this origin. We know that at one time this region was under water and possibly subjected to strong tidal currents of a fixed direction. We may also assume that volcanic emissions of gases or hot water might have caused many large centers of disturbance in this vicinity. These conditions, together with the sandy soil would possibly be the cause of these large shallow elliptic craters. The extremely low height of the rims would have to be explained by extensive subsequent silting action. The double and triple rims in the case of some of the Carolina "Bays" agree also in general with the smaller secondary sand rings which occur with the laboratory "sand-craters." It is realized that this hypothesis of origin of the Carolina "Bays" is subject to many criticisms but it is offered as another possible explanation of these interesting and unique formations.

19. In conclusion the statement is again made that this simple laboratory method of making "sand-craters" may have been presented by other writers, and if this is the case apologies are offered for not mentioning their names. The similarity of these "sand-craters" with respect to lunar craters is considered as quite important and definite although the conditions surrounding the origin of the lunar craters may have varied to some extent from the method presented in this paper. It is suggested if possible that experiments with "sand-craters" be continued on a much larger and more complete scale than described in this paper as the comparisons will surely be found to be both interesting and valuable to the science of geology and astronomy.

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A GENETIC SYSTEM OF EARTHQUAKE-ORIGIN

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Seismology has moved in recent years into the foreground of geological research. The contacts between the two scientific fields are numerous and important as recently demonstrated by Macelwane [see 1 under section "References" at end of paper]. While structural geology could get reliable data from the seismological records, dynamic geology has been benefited with comparatively few facts. We have, however, to visualize that the earthquakes are evidence of acting geological forces. Although all geological events are customarily gaged in a scale of millions of years, it may be stated that the slow and imperceptible, mostly even unmeasurable, geological process culminates frequently in earthquakes which are events accessible to observation--sometimes too fatally obvious.

One may raise the question as to what place in the system of dynamic geology the earthquakes really belong, principally as the occurrence of certain types of earthquakes have been used as an argument for or against geologic theories, especially in the case of deep-focus quakes as related to the theory of isostasy [2, 3]. In the first place it has to be realized that earthquakes are of widely different origin but in the past seismologists have simplified the issue by classifying only three general categories, which Sieberg [4] as main authority gave as tectonic, volcanic, and cave-in earthquakes. The detection of the deep-focus earthquakes has already brought some confusion into this simple system because instead of a cause there is now a more seismometrical fact introduced as a significant feature. From the seismologist's viewpoint even the secondary reasons for earthquakes, the numerous trigger-forces, which release the accumulated stresses might serve as a basis for classification. If we accept Macelwane's [1] statement that the causes of earthquakes are still a wide-open problem it seems to be a bold attempt to classify them at all. Nevertheless, a certain grouping of the events, even if preliminary, incomplete, and challengeable in detail, may help to clarify and to bring some order into the observations. For this matter seismology may take advantage of geological conceptions with the necessary reservatio mentalis as regards some contested theories in this field.

One fact may be regarded as generally accepted, namely, that there exist on the Earth two types of zones according to their geological behavior, one where the acting forces are extremely slow, where major geological upheavals have not happened for a long period, and others, where relatively fast motions and changes in structure are to be observed. Side by side we have motions of orogenic and of epirogenic type. The motions observable in the crystalline crust of the Earth are due to causes which, at least partly, have their origin in the elastico-viscous substratum, to use the terms of Daly [5]. So far as the participation of this lower layer in making geological history is concerned, it seems to be differentiated also according to the two zones. In the orogenic zones it plays an active part, while in the epirogenic zone it seems to be mainly passive. The subcrustal activity in the zone of mountain-building, whether we call them subcrustal currents in the sense of Ampferer [6] and Schwinner [7] or thermal convection as Holmes [8] puts it, is witnessed by the deep-focus earthquakes which indicate changes and motion. It is irrelevant for our present deliberations to what we attribute these motions. Volcanic activity is another sign of these zones and in the outer crust we find horizontal movements as one of the characteristic features accompanying the mountain-formation. On the other hand, there is no indication of any active motion in the subcrustal material in the epirogenic consolidated areas; there are no appreciable horizontal movements to be observed, while vertical motions are prevailing. This latter type might be attributed to isostatic adjustment. The theory of isostasy is still so largely contested that our statements concerning it have to be carefully weighed. It is generally accepted that we have a specific light crustal material floating on a specific heavier one. This fact would mean even if we deal with solids that changes in mass-distribution in the upper part will tend to become gravitationally compensated in a rotating body like the Earth. The only open question is at what rate this adjustment would take place. As the subcrustal material will be highly viscous in any case there has to be an appreciable lag in the compensation-movement so that we may say isostatic equilibrium is merely the final, so to say, ideal state. The ever-working and fast-working dynamic forces, erosion and sedimentation, change the outer crust and the isostatic adjustment tries slowly to balance their effects. This will work fairly well if the subcrustal material itself is at rest. As soon as it is itself in motion, the forces which produce this motion will tend to obscure or even prevent isostatic adjustments. Therefore, since we had to assume an active part of the subcrustal material in orogenic zones, isostasy will be of minor importance until the zone gets to rest. This is quite in accordance with statements made by R. T. Chamberlin [9] regarding isostasy. It accounts perhaps also for the findings of Dahm emphasized by Macelwane [1] that seismometrical data show horizontal differences in the subcrustal material. This, however, does not exclude isostatic adjustments between old blocks and their heavier underlying subcrustal material. We get therefore a scheme which is represented in Table 1. It remains now to be seen how the different observed types of earthquakes fit into such a dualistic scheme. In the first place, we have to single out the cave-in earthquakes which disregard the zonal differences; they may happen everywhere, provided there exists any hollow space in the crustal zone. According to our present knowledge

Table 1

Agent	Orogenic zone	Epirogenic zone
Subcrustal material	Active	Passive
Crustal motions	Every direction	Vertical
Total movement	Kinetic	Isostatic
Earthquakes	Crustal and subcrustal	Crustal

they are negligible in number compared with the total number of earthquakes, are weak in effects, and are principally observed in regions where larger layers or deposits of water-soluble material are present.

In the epirogenic zone we observe two types of earthquakes which are both to be explained by the upward and downward adjustment-movements. They are frequent in places where we have differential movement of two blocks side by side. The opposing directed forces accumulate stresses which are released along planes of weakness as represented by old faults -- faulting-quakes are the result. Besides these, new break-lines may develop and rupture-quakes will occur. The faulting quakes are usually single events, in many cases not even producing aftershocks while the rupture-quakes have the tendency of happening in whole showers or swarms. The focal depth of both types usually does not exceed 30 to 50 km and is in many cases even closer to the surface. The relationship between vertical motions of isostatic type and earthquakes has been well demonstrated in the cases of Scandinavia, France, and Germany [10].

In the zones of mountain-formation the active participation of the subcrustal material gives reason for other kinds of earthquakes. Here are the localities where the deep-focus earthquakes are observed. We do not have sufficient evidence to formulate a conception implying faulting or similar motion as reason for these quakes. At the present it seems more likely that either phase-change in the physico-chemical sense or recrystallization is responsible for this type of quakes. This needs not to be an explosive event if the subcrustal material has only a fair amount of rigidity, which is probably the case. Then the physical or chemical change may take place over a longer period of time, creating inhomogeneities which may be even larger hollow spaces in case of volume-decrease or high pressures in case of volume-increase. In a rigid material such stresses will be released much in the same way as in surface quakes by secondary forces. Such a conception would make it easier to account for certain observed periodicities of the deep-focus quakes and also account for the fact of repetitions from certain foci, if the stresses are only partly released.

Next and also characteristic for the orogenic regions are earthquakes connected with volcanic activity. The first type, namely, eruption-quakes needs no special discussion as they do not differ from vibrations produced by any kind of explosion. Furthermore there exist earthquakes closely associated with volcanism, originating in deeper layers of the crust, although not much about their exact mechanism is known. Branca [11] connected them with intrusions and pending further verification we may at least tentatively reserve some space for them in the scheme. Finally there remain the earthquakes which are the most important from our human viewpoint, due to their violence, the great tectonic earthquakes of the zone of mountain-building. There again we have block-movements but this time due to the forces of mountain-formation, bulging and buckling the crust. The resulting stresses are consequently larger than the moderate ones, which we observe in the epirogenic zones. The restoration of a state free of stress is more difficult; the adjustments go on for a longer period as evidenced by the numerous aftershocks of each major earthquake. These quakes may be termed as orotectonic earthquakes. Thus we get the picture of Table 2

Table 2

Zone	Type of quake	Depth in km	Character	Cause
Epirogenic	Cave-in		Weak	Lack of support
	Faulting	0-50	Single, moderate shock	Isostatic movements
	Rupture	0-50	Swarm of moderate shocks	Isostatic movements
Orogenic	Cave-in		Weak	Lack of support
	Deep-focus	100-1000	Moderate on surface	Physico-chemical change?
	Eruptive	0-10	Weak	Explosion
	Intrusive	10-50	(?)	Magmatic changes?
	Orotectonic	10-50	Destructive with many aftershocks	Mountain-formation

Finally it seems to be worth while to call attention to the interaction of different earthquake-types. Adjustments at one place may release shocks elsewhere -- a phenomenon usually called resonance. Equally important are reactions which have a longer lag in time. If the deeper layers are disturbed it cannot be helped that the upper layers are affected too. If one end of a block is moved the other will have to come to a new equilibrium-position as well. It can be shown that earthquakes themselves condition other earthquakes, which are not simply aftershocks and this angle should be considered in the future.

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RELATION OF EARTHQUAKE-BELTS OF THE PACIFIC AND INDIAN OCEANS TO SUBMARINE TOPOGRAPHY

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It has often been pointed out that earthquakes are chiefly associated with mountain-building and with deep ocean-troughs. This is quite true when applied to the greater portion of the two major earthquake-belts and especially in the case of the major earthquakes.

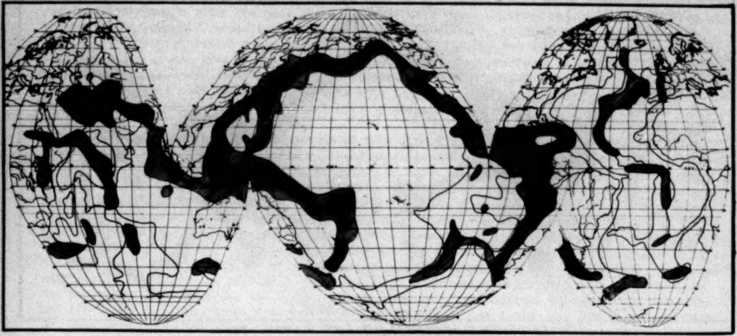
However, the Mid-Atlantic Ridge is a definite exception. In The origin of the Mid-Atlantic Ridge, by Henry S. Washington (Maryland Acad. Sci., v. 1, no. 1, 1930) it is stated that the Ridge is a submerged mountain-ridge of a type different from any other on the Earth. In general it is less than 12,000 feet beneath the sea with some parts less than 9000 and with a few volcanic islands rising 3000 to 4000 feet above the sea. Its general height above the surrounding ocean-floor is between 3000 and 6000 feet with a few island-peaks rising 18,000 to 20,000 feet.

There is little known evidence of the existence of deep troughs in the vicinity of the Ridge. There are a few deep soundings in the region of the equator where the greatest seismic activity occurs but the soundings are too few to indicate whether or not troughs exist. In any case the earthquakes are associated with a rise or Schwelle.

There has been some question whether there is similar association with rises in other oceans. The author pointed out this possibility as regards the Indian Ocean in his article "A new map of earthquake-distribution" in the Geographical Review for January, 1935 (p. 128). Such an investigation would have been useless a short time ago because of lack of information about the submarine contours. As an example of this, H. Rehm in a recent article (Die Erdbebentätigkeit der Weltmeere Sowie Ihre Beziehungen zur Tektonik) has the Schwellen or rises outlined in such a general way that the significance is not brought out.

In 1935 Dr. G. Schott included in his book on "Geographie des Indischen und Stillen Ozeans" a map in colors which gives through certain contours the depth of the Pacific and Indian Oceans according to the latest available information. He adopted 4000 meters as boundary between the Schwellen and the ocean-bed. The earthquake-information from Rehm's map was plotted on this (see Fig. 1) and it was at once seen that there is a definite relation between depth and general earthquake occurence, which in part has not heretofore been brought out for these oceans.

The plotting of the major belts brought out no new information of special interest since the features they are associatied with are well known. However, in the branches of the belts and detached areas, both of which have very few major earthquakes, there appears a very definite relation between rises as defined by the 4000-meter curve and earthquake-occurrence. It will be seen that nearly all of the activity is confined to the rises. This does not mean that there has been earthquake activity over all the area of the rises. The nature of the available data should not be forgotten. There are many earthquakes listed in the International Seismological Summary which cannot be located and some of these may be in these areas. The distribution of seismograph-stations is not well suited for locating the lesser earthquakes of these regions. The total period of determination of submarine earthquakes is not in excess of 25 years and many of the determinations have



DISTRIBUTION OF EARTHQUAKES
[HEAVY CROSS-HATCHING INDICATES MAJOR EARTHQUAKES RECORDED THROUGHOUT THE EARTH; LIGHT CROSS-HATCHING INDICATES ALL OTHER EARTHQUAKES WIDELY RECORDED ON INSTRUMENTS; CONTINUOUS LINE BOUNDS AREAS WITH DEPTH LESS THAN 4000 METERS]

been only partly satisfactory. The surprising fact is that there is such definite correlation.

In only one case does there seem to be an important area in a region indicated as a deep though in this case there is a rise very near. This is a small but active area southeast of Madagascar. It is possible that further soundings might develop either a rise or a deep ocean-trough and perhaps more likely the latter.

There are a number of scattering earthquakes not shown since only those occurring in groups have been placed on the map. The number is not large. Some of these occur in the deep basins. It should be understood that there is no intention to deny the occurrence of earthquakes in depths greater than 4000 meters except in the deep troughs but to point out the tendency against such occurrence.

No attempt will be made to discuss the geological significance. It is of interest to point out that this comparison could have been made only within the past few months, for the complete information needed was not available in usable form.

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REVIEW OF EARTHQUAKES FOR THE PAST YEAR

E. W. Eickelberg

It is rather difficult to compile accurate statistics in April for the period of twelve months ending March 31, 1936. We can give the number of epicenters determined by the Jesuit Seismological Association and the U. S. Coast and Geodetic Survey in cooperation with Science Service and numerous universities and others, but this does not include the whole mass of information collected by agencies in other countries but not yet available. All disastrous earthquakes are not world-shakers and, therefore, many important earthquakes occur whose epicenters are not determined by agencies in the United States.

The average number of immediate epicenters determined by the U. S. Coast and Geodetic Survey and Jesuit Seismological Association in cooperation with Science Service for the past four years is 58, whereas in the past year there were only 23. On the other hand, 50,000 people were killed during the present year as compared to 130 in the preceding year, showing that earthquake-statistics for any one year are meaningless except to show that there is wide range in their number, severity, and destructiveness.

Dr. Charles Davison in a recent article in Nature (v. 137, p. 605, 1936) estimates that the

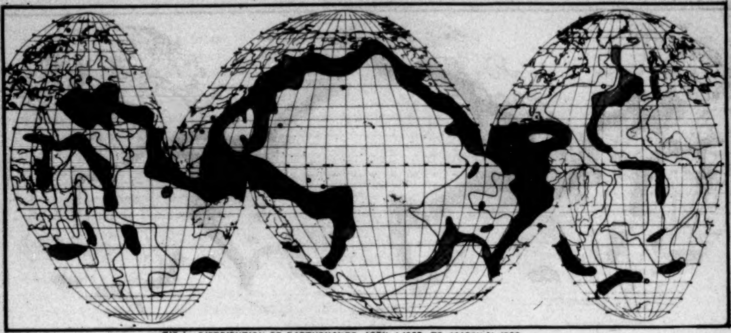

FIG. 1—DISTRIBUTION OF EARTHQUAKES APRIL 1, 1935, TO MARCH 31, 1936
SMALL CIRCLES INDICATE EPICENTERS

total number of deaths in earthquakes during the past two centuries averages 28,000 per year. The average annual rates for certain important earthquake-districts, he gives as follows: 13,862 in China; 7980 in Colombia and Ecuador; 2240 in Japan; 1006 in Italy; 991 in Central America; 715 in India; 586 in Persia; 550 in Asia Minor; 99 in Greece; 35 in the Philippines; 29 in Formosa, and 6 in the United States. A few districts, such as Spain, Portugal, Venezuela, and Algeria, are not accounted for but, grouping them together, the corresponding number of lives lost per year is 380. The sum of all the districts is 30,479. This is an enlightening summary and may be taken as one of the reasons for the continued interest in the earthquake-problem.

As will be seen from Figure 1 the distribution of the earthquakes during 1935-36 is quite normal, possibly one or two earthquakes falling out of recognized earthquake-zones. In the United States itself we consider California as furnishing our most important laboratory for earthquake-study. However, during the calendar year 1935 there were ten earthquakes which caused some damage. Eight of these occurred outside of California, two in Montana, two in Arizona, one in New Mexico, one in Nebraska, one in Georgia, one in Canada -- the last shook the entire northeastern section of the United States, causing some damage in New York State.

There are three outstanding earthquakes for this past year. The first occurred April 21, 1935, in northwestern Formosa. The second occurred May 31, 1935, at Quetta, India, and the third occurred October 18, 1935, in Montana. The Canadian earthquake of November 1, 1935, was felt over an area of probably 650,000 square miles, but only slight damage resulted except in the area of the immediate epicenter which was very sparsely populated. In the Formosa earthquake 3410 people were killed, 12,000 were wounded, 17,900 houses were destroyed, and 21,400 houses partly collapsed or were severely damaged.

The houses of this section are of two types, namely, the usual wooden houses of Japan and those of brick and mud-blocks cemented with mud-mortar with roofs of thatched straw or Formosa tile. The latter are excellent protection from heat but can not withstand violent earthquakes. The ratio of the percentage of wooden houses destroyed against the mud-brick type was as one is to six in spite of deterioration of wooden houses by the work of the white ant. From evidence on the surface it has been determined that the relative horizontal movements were as great as 1.4 meters and the vertical movements ranged from 0.5 to 2.5 meters. From the estimated value of acceleration (less than one-third gravity) T. Suzuki, J. Astron. Geophys. v. 13, no. 1, pp. 55-59, 1935) says that this earthquake was not as strong as the Tango earthquake of March 1927 or the North Idu earthquake of November 1930.

Reporting on the Quetta earthquake, W. West, Assistant Superintendent of the Geological Survey of India, gives the following information (Records of the Geological Survey of India, v. 69, part 2, pp. 203-240, 1935): "From the point of view of the number of lives lost the Quetta earthquake is considered the most disastrous within historic times. Like all Baluchistan earthquakes this was of shallow focus, about five miles and, therefore, not felt over a large area (100,000 square miles) as compared with nearly 2,000,000 square miles for the North Bihar earthquake of 1934. About four shocks were felt in the epicentral zone in the preceding ten weeks and about ten seconds preceding the main shock a slight tremor was felt by a sentry, Quetta being a strongly fortified region. Sixty hours after the main shock a severe aftershock occurred which, had there been any houses left to destroy, would have completed the destruction." Although this earthquake occurred in the early morning hours it was observed, nevertheless, by those participating in military maneuvers at the time of the earthquake and about four miles north of Quetta. The ground-motion was described as like "a terrier shaking a rat." "The ground heaved as in a raging sea or as the way a small boat behaves in the wake of a large storm. Those who did not lie down at once were either flung down or were just able to stagger about."

The towns of Quetta, Mastung, and Kalat were almost entirely razed. Twenty-six thousand out of 40,000 population were killed. Including those who were killed in the surrounding villages, the total loss of life runs up to 40,000 or more. This enormous loss of life was due largely to poor construction and narrow streets. Some new governmental buildings collapsed, and examination proved failure was due to an inferior quality of mortar. Destruction was greater near the junction of rock and alluvium than in the central area of alluvium. The author states this was probably due to the greater disturbance caused by the different periods of vibration of the two types of material. Damage was also greater on wet alluvium than on dry, water aiding in the transmission of the shock. Wire-netting in plaster caused many people to become trapped and made rescue difficult and self-help impossible. An interesting illustration is the effect on two bungalows located across the street from one another, one designed as earthquake resistant and the other not. No damage occurred to the former, while the latter was completely destroyed. Mr. West recommends buildings of one story, square in shape. Some buildings had galvanized-iron chimneys above the roof-levels. Such chimneys stood while the brick-chimneys fell.

The Montana earthquakes of October 18 and 31, 1935, killed six persons and did property damage to the amount of $5,500,000. Dr. D. S. Carder of the United States Coast and Geodetic Survey was an eye-witness of the second shock. Part of his report is quoted herewith:

"On the morning of October 31, I investigated some solid waves which were caused by the earthquake of October 18 with Ray Hofstatter of the Montana Power and Light Company. At 11:37 a.m., Mountain Standard Time, we had just returned to the Federal Building and as we were discussing the previous earthquake while sitting in Mr. Hofstatter's parked car, which was facing north, a sharp blow came from the northeast and deep underground and a second later the car began a violent rocking from side to side. The rocking was immediately preceded by a second hard blow. At the time I was thinking of the fine record we were getting and of a brick-wall hidden by an awning just across the sidewalk. The latter, however, was quite safe. Otherwise I was not frightened but was highly excited. After the heavy shaking subsided, I took my leave to tend the instruments.

"The ground continued to tremble for several minutes and strong aftershocks were frequent. Business activity was demoralized and it was reported that several thousand people, especially women and children, evacuated the city. The unrest of the ground seemed to continue throughout the day and into the night with repeated low rumblings, many of them not accompanied by perceptible shocks.

"The amplitude of the ground in the frequency of the greatest agitation was probably no more than one or two mm, yet the upper floors of some of the buildings must have swayed an inch or more; some observers say a foot or more though this may be exaggerated. All observers agree that poles and trees swayed violently. Some observers claim they saw waves allegedly a foot high and 50 or 100 feet from crest to crest in the streets.

"The earthquake of October 31 caused considerable new damage to buildings apparently untouched by the former hard tremors, although it is possible that many of these had already been weakened. Earlier damage was greatly accentuated. Several buildings which had been badly hit by the former tremor were completely demolished on the 31st and many others were rendered uninhabitable."

As in the Long Beach earthquake the schools suffered severe damage and the time of occurrence was again fortunate in that these buildings were unoccupied. The new $300,000 building, normally occupied by 1000 students, is practically a total loss. Had the times of occurrence of these two quakes been reversed, loss of life and suffering would have been enormous. It is as though Nature has sounded her warning for the people to look to the safety of their school buildings and other public gathering places. We can not hope to always be as fortunate in the time of occurrence of earthquakes as we were in those of Long Beach and Helena.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REFLECTION DIP-SHOOTING METHODS IN SEISMIC PROSPECTING

H. M. Rutherford

Most writers on reflection-methods in seismic prospecting base their interpretations on a calibrated velocity. This is to say they assume for the purposes of computation an isotropic and homogeneous overburden. This conception has proved fruitful in practice because it reduces the computations to a minimum. This does not imply, however, that the interpretations can only be made by use of an average velocity.

When the reflection-method was first put into use the object was to map some particular marker. For instance, depths would be computed on a limestone, for example, the Viola Lime in Oklahoma, and these plotted on a map. Contours would be drawn and thus the presence of a structure might be detected. This method would not work, however, in the Gulf Coast Region of Texas, for there were no beds which could be correlated by this method over a wide region. This gave rise to the so-called "dip-method" of reflection-shooting. In this method the seismograms were interpreted for reflections and from these data the dip of the bed which caused the reflections was computed. No depth-calculations were essential. The basic principles of this method have been given by the present author in a previous paper (H. M. Rutherford, Reflection-methods in seismic prospecting, Geophysical Prospecting, Amer. Inst. Mechanical Engineers, 1934).

Consider the situation as depicted in Figure 1. In this Figure O is taken as the origin of a disturbance, such as that caused by a dynamite-blast. P_1, P_2, and so on are the points at which energy is reflected from the interface shown. The distances from O at which the respective reflections are recorded are X_1, X_2, and so on. I is the image-point of the reflections. The interface slopes to the surface at the angle w. θ is the angle between the normal to the interface and the surface. It is easily seen from the Figure that

$$V^2t^2 = X^2 + 4H^2 - 4HX \cos \theta$$

or

$$V^2t^2 = X^2 + 4H^2 + 4HX \sin w$$

where t is the time corresponding to the distance X, taken in the direction of increasing depth of the interface. In case we shoot "up-slope," that is, the distances increase with decreasing depth of the interface, we have

$$V^2t^2 = X^2 + 4H^2 - 4HX \sin w$$

This can be put in the form of a hyperbola by multiplying $4H^2$ by $(\sin^2 w + \cos^2 w)$, and factoring, or

$$t^2/(4H^2\cos^2 w/V^2) - (X \pm 2H \sin w)^2/(4H^2 \cos^2 w) = 1$$

where the plus sign corresponds to shooting "down-slope" and the minus sign means shooting "up-slope." From this it is seen immediately that we get the minimum time and distance when we shoot "up-slope" and the time and distance will be given by

$$X = 2H \sin w$$
$$t = 2H \cos w/V$$

Thus as we shoot "up-slope" from the shot-point the time of reflection will decrease with increasing distance up to the distance which is equal to 2H sin w. Beyond this point the time will increase with increasing distance.

It will be noticed that the slope can be told qualitatively immediately from the record. If the bed slopes up from the shot-point, the reflection-times will be less and less with increasing distances, provided the distance does not exceed 2H sin w in amount. If down, the reflection-times will be greater with increasing distances. Curves can be graphed from the foregoing equations or approximate formulas can be devised for field-use which will give the slope.

In actual practice profiles are shot across country. If there occurs a reversal in dip, then an anomaly is present. By taking enough strikes and dips the structure can be drawn in.

The author has presented elsewhere a method for mapping structure in the case of horizontal beds by assuming an overburden which has a velocity which varies with the depth below the surface (The interpretation of reflection-seismograms, Trans. Amer. Geophys. Union, June 1933). In

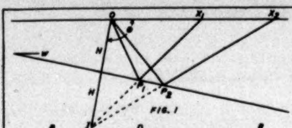

FIG. 1

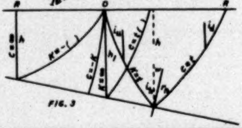

FIG. 3

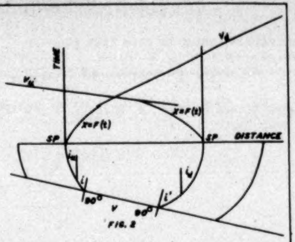

FIG. 2

another paper he gives an actual example where the velocity-depth function is determined and used to compute a depth (A formula for weathering correction, Trans. Soc. Pet. Geophysicists, v. 5, March, 1935). It is the purpose here to develop a method whereby the slope and the depth can be determined from reflected phases which are caused by a discontinuity which slopes to the surface and which has an overburden in which the velocity varies as the depth below the surface.

We will assume, in what follows, that we have already determined the velocity-depth function in each case. An actual example of the determination of this function will be given. If we consider a refraction-profile shot "down-slope" it is easy to show that the incident ray will make an angle with the normal such that

$$\sin i_u = V(y)/V_u$$

If we shoot in the opposite direction we have

$$\sin i_d = V(y)/V_d$$

where V_u is the velocity obtained by shooting "up-slope" and V_d is the velocity obtained by shooting "down-slope." These velocities are "apparent." Figure 2 shows the situation. These rays will travel such a path that the angles in question are the "critical angles."

Suppose that instead of V_u and V_d we write K and C, that is,

$$\sin i_u = V(y)/K$$

$$\sin i_d = V(y)/C$$

The above means that the ray-path will strike a hypothetical bed at the critical angle whose velocity shooting up is K and whose velocity shooting down is C.

The above considerations suggest a way to obtain all the possible reflected paths from a discontinuity. If we take the depth of the discontinuity below the surface as h, we have then, if

$K = V_u$ and $C = V_d$	$i_h, r_h = i_c$ (critical angle)
$K < V_u$	$i_h, r_h > i_c$
$K > V_u$	$i_h, r_h < i_c$

Thus if we consider all possible values of K, and hence of C, we will describe all possible reflection-paths.

In Figure 3 consider a ray-path which originates at O and after reflection at the point P returns to the surface and is recorded at the point R. Call the depth of P below the surface, h. Then the time to travel this path is given by

$$T_r = t_{OP} + t_{PR}$$

or

$$T_r = \int_0^h K\,dy/(V(y)\sqrt{K^2 - V^2(y)}) + \int_0^h C\,dy/(V(y)\sqrt{C^2 - V^2(y)})$$

The distance corresponding to this time is

$$X = \int_0^h V(y)dy/\sqrt{K^2 - V^2(y)} + \int_0^h V(y)dy/\sqrt{C^2 - V^2(y)}$$

Note in Figure 3 that at depth h, where i, r are the angles of incidence and reflection, respectively, at this depth, i = r

$$\begin{array}{c} i = i_u + w \\ r = i_d - w \\ \hline i_d = i_u + 2w \end{array}$$

We have

$$\sin i_d = \sin (i_u + 2w) = \sin i_u \cos 2w + \sin 2w \cos i_u$$

Since

$$\sin i_d = V(h)/C$$

$$\sin i_u = V(h)/K$$

we obtain by substitution

$$V(h)/C = V(h)/K \cos 2w + \sqrt{K^2 - V^2(h)}/K \sin 2w$$

hence

$$C = (K\,V(h))/(V(h) \cos 2w + \sqrt{K^2 - V^2(h)} \sin 2w)$$

In the case where $w = 0$, $C = K$ and

$$T_r = 2\int_0^h K\,dy/(V(y)\sqrt{K^2 - V^2(y)})$$

$$X_r = 2\int_0^h V(y)dy/\sqrt{K^2 - V^2(y)}$$

We will now consider in some detail the equation which gives the relation between the two parameters C and K and the angle of slope, w. If K be taken as infinite (positive), then the ray will leave the shot-point orthogonal to the surface, that is, $i_u = 0$. In this case we have

$$C = V(h)/\sin 2w$$

and as a consequence $i_h = r_h = w$. Note that i_u is taken positive measured from the vertical to the right and that i_d is measured positive to the left of the vertical. If C be taken to be infinite it will be seen that we are shooting "up-slope" and

$$K = V(h)/\sin(-2w)$$

If we are shooting "up-slope" we have

$$C = K\,V(h)/(V(h) \cos 2w - \sqrt{K^2 - V^2(h)} \sin 2w)$$

If C and K are taken equal but opposite in sign, then we have a ray-path which is reflected from the discontinuity such that it strikes it orthogonally. This will happen when we take

$$K = V(h)/\sin w$$

Note that since the bed is sloping the proper value of h must be substituted in the time- and distance-integrals. If we take the distance O to P to be h_1 when K is infinite, we have

$$h = h_1 + [\int_0^h V(y)dy/\sqrt{K^2 - V^2(y)}] \tan w \quad \text{"down-slope"}$$

$$h = h_1 - \left[\int_0^h V(h)\, dy/\sqrt{K^2 - V^2(y)} \right] \tan w \quad \text{"up-slope"}$$

If only small distances be taken on the surface, that is to say K is large, then the last term can be neglected. Or, if w is sufficiently small the second term can be neglected.

We consider a simple example. Suppose that the velocity-depth function is such that $V(y) = V$, a constant. Let the angle of slope, $w = 10°$ and the depth OP be 5000 feet. We have then

$$t = \int_0^h C dy/(V\sqrt{C^2 - V^2}) + \int_0^h K dy/(V\sqrt{K^2 - V^2})$$

$$x = \int_0^h V\, dy/\sqrt{K^2 - V^2} + \int_0^h V dy/\sqrt{C^2 - V^2}$$

$$h = h_1 + \left[\int_0^h V dy/\sqrt{K^2 - V^2} \right] \tan w$$

From which we obtain, after integrating

$$t = hK/(V\sqrt{K^2 - V^2}) + hC/(V\sqrt{C^2 - V^2})$$

$$x = Vh/\sqrt{K^2 - V^2} + Vh/\sqrt{C^2 - V^2}$$

$$h = h_1/(1 \pm V/\sqrt{K^2 - V^2} \tan w)$$

In the last expression, the plus refers to "up-slope" and the minus to "down-slope." We take $h_1 = 5000$ feet, $w = 10°$, and $V = 10{,}000$ feet/second. If we choose $K = +100$ then C will be 23.026905. We will be shooting "down-slope" and the distance will be 2966 feet and the time 1.0767 seconds. With $K = -100$ then $C = 40.594861$ and we will be shooting "up-slope." The time and distance are $X = 755$ feet and $T = 1.00068$ seconds. If we take $K = -57.5871$, that is to say

$$K = -V/\sin w = -\ 10/\sin 10° = -57.5871$$

(In all the calculations kilo-feet was used instead of feet.) The value of C will be for this value 57.5871. This assures us that the reflection will take place orthogonal to the reflecting surface. The time and distance will be $X = 0$ and $t = 0.98481$ second. Consider now the minimum time and distance. This will be such that C = infinity. Thus the value of K will be $K = -V/\sin 2w = -29.238056$ and C = very large (infinity for all practical purposes). The time and distance will then be $X = 1.710$ kilo-feet and $t = 0.96985$ second. All of these figures can be obtained, of course, from the formula as given before

$$V^2t^2 = X^2 + 4H^2 \pm 4HX \sin w$$

The method as outlined would not be the best way to calculate the simple case just cited. Its value lies in the more complicated problems connected with a velocity-depth function which cannot be represented by a constant. Many examples might be given but we restrict ourselves to just one on account of space.

The writer has found several areas in which the velocity-depth function could be closely approximated by $V = ay^{1/2} + b$. In a region in Oklahoma the time-distance relationships could be expressed by $X = 0.711519\, t^2 + 5.172t$ where the constants are given in kilo-feet. By the well-known formula for penetration versus velocity it was found that

V in feet/sec	Depth in feet	V in feet/sec	Depth in feet	V in feet/sec	Depth in feet
6000	341	6600	785	7200	1350
6200	474	6800	961	7400	1563
6400	623	7000	1149	7600	1787

A function of the form $V = ay^{1/2} + b$ fits these data thus

$$V = 2.130239\, y^{1/2} + 4.7292 \qquad \text{RMSE} = 16 \text{ feet/sec}$$

All measurements are in kilo-feet.

For a function of this form the time-distance relations are

$$T_r = \int_0^h \frac{K\,dy}{(ay^{1/2} + b)\sqrt{K^2 - (ay^{1/2} + b)^2}} + \int_0^h \frac{C\,dy}{(ay^{1/2} + b)\sqrt{C^2 - (ay^{1/2} + b)^2}}$$

$$X_r = \int_0^h \frac{(ay^{1/2} + b)dy}{\sqrt{K^2 - (ay^{1/2} + b)^2}} + \int_0^h \frac{(ay^{1/2} + b)dy}{\sqrt{C^2 - (ay^{1/2} + b)^2}}$$

$$h = h_1 \pm \int_0^h \frac{(ay^{1/2} + b)dy}{\sqrt{K^2 - (ay^{1/2} + b)^2}} \tan w$$

The reader can perform these integrations quite easily by making the substitutions $u = ay^{1/2} + b$ and $dy = 2(u-b)du/a^2$. The resulting formulae are somewhat long and will not be written here. In spite of the apparent length of calculations the formulae can be used to a good advantage to plot graphs. These graphs can be used in the field to determine the dip of the reflecting horizon.

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TRANSFORMING THE STEREOGRAPHIC MAP

F. W. Sohon

The stereographic projection, because of the simplicity and elegance of its mathematical properties, has been a mathematician's playground ever since the time of Hipparchus. In endeavoring to explain some of its properties a few years ago, I chanced to hit upon several that certainly do not seem to be well known. One of these "The rule for longitude" was announced in a paper read by Father Buckley at our Fordham meeting two years ago. Another property, concerned with transforming the projection, forms the subject of the present paper. It is well known that the stereographic projection can be transformed into either an orthographic, or gnomonic, or equal-area, or equal-distance map, merely by displacing the points radially. These are transformations of the stereographic map into other maps possessing other properties. In this paper, however, we are interested in another sort of transformation. We must first digress to explain the concept of inverse in a circle.

Inversion in a circle is a problem in plane geometry. In a plane, one point is said to be the inverse of another point with respect to a given circle (or straight line) if every possible circle (or straight line) drawn through the first point orthogonal to the given circle (or given straight line) also passes through the second point. When two points are inverse with respect to a given straight line (see Fig. 1), they are symmetrical with respect to that line. If two points are inverse with respect to a circle (see Fig. 2), they lie upon the same radius of the circle, but their position is such that the product of their distances from the center of the circle is equal to the square of the radius of the given circle. We can also explain the matter in a different way. If we draw the diameter of the given circle which passes through the point whose inverse is required, and place on the opposite end of the diameter a concave mirror whose principal focus lies at the center of the circle, then the image of the given point in the concave mirror will be the inverse of the given point with respect to the given circle.

With a circle given, the inverse of any point can thus be found readily enough by measuring its distance from the center of the circle, dividing the square of the radius of the circle by the quantity just obtained, and laying off the quotient along the radius in the direction of the given point. The inverse can also be found geometrically as follows: In Figure 3, let C be the center of the given circle and P be the given point. Draw any other arbitrary radius of the circle CQ, then from the point R, where line CP cuts the given circle, draw RS parallel to PQ intercepting CQ in S. Lay off CT on CP equal to CS, then the point T will be the inverse of the point P with respect to the given circle, as is evident from the similar triangles, CRS and CPQ. If we refer to Figure 4 instead of Figure 3, the construction will be found for a point that is given inside the given circle. The same identical construction applies to Figure 4 without any change whatsoever. Of course, if the point is given on the circumference of the given circle then it coincides with its own inverse.

Let us now consider two points that are given on the surface of a sphere. If one of these points is the image of another point with respect to a plane of symmetry through the center of

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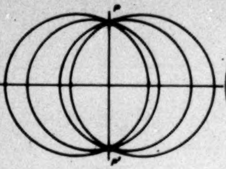


FIG. 1

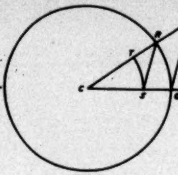


FIG. 3

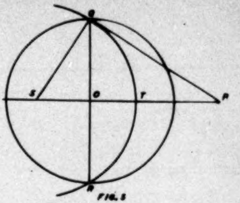


FIG. 5

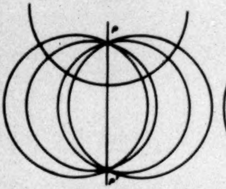


FIG. 2

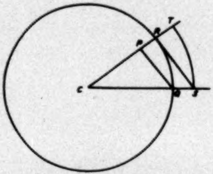


FIG. 4

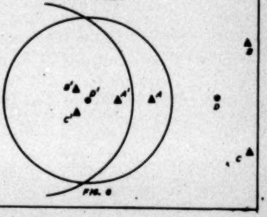


FIG. 6

the sphere, then every circle on the surface of the sphere which passes through both will have its pole on the great circle in which the plane of symmetry cuts the sphere; and consequently, all circles through both points cut the great circle in question orthogonally. Now the stereographic projection is conformal. Circles are projected as circles or as straight lines, and angles are projected true. Hence, if two points on the surface of the sphere are symmetrical with respect to a given plane, their projections will be mutually inverse with respect to the circle (or straight line), which is the projection of that great circle which the plane of symmetry traces on the surface of the sphere.

This principle can be used to change the zenith of the map. Referring to Figure 5, let it be required to transform the stereographic map so that the point whose projection is P will be the zenith of the new map. Let O be the center of the primitive circle, then P and O must be mutually inverse with respect to a circle which is the projection of a great circle. Draw the line OP and the diameter QOR of the primitive circle perpendicular to OP. Draw QS perpendicular to QP, intersecting OP in the point S. Then since SQ^2 is equal to SO multiplied by SP, the points Q and P will be inverse with respect to a circle QTR, whose center is S and whose radius is SQ. This circle will be the projection of a great circle because it passes through the two points, Q and R, which are situated at the extremities of the diameter of the sphere. If we now invert all of the points of the map in the circle QTR, we shall have the projection of a configuration of points on the surface of the sphere that is symmetrical to the original configuration, and the point whose projection was originally the point P has now become the zenith of the map. If we refer to Figure 6, the construction has been carried out so as to make D' the inverse of the point D fall at the center of the primitive circle. A', B', and C' were then found as the inverse of A, B, and C, respectively. It will be observed that the new map has the defect that it is obtained by reflection in a plane, instead of by a rotation, and that consequently it is drawn in reverse. This can be remedied by taking its mirror-image, or by holding the paper to the light and looking at the new map from the back.

Georgetown University,
Washington, D. C.

THE DETERMINATION OF GROUND MOTION FROM SEISMOGRAMS

A. Blake

(Abstract)

The greatest source of error in determining the motion of the ground from a seismogram is the inaccuracy which enters in determining the position of the center of oscillation of the seismometer-pendulum as a function of the time, that is, the error of recording and scaling. This error becomes large in the strong-motion problem as the period of the pendulum recedes in either direction from the range of interest; this conclusion is not dependent on the assumption that the motion is of simple harmonic type.

Denoting by x_1 the displacement of the seismometer, by x_2 the corresponding quantity for a damped normal component of a building subjected to the ground motion, and by x the displacement of the ground, we may write the seismometer equations in the form

$$(D - r_1)\ (D - r_1')\ x_1 = -D^2x = (D - r_2)\ (D - r_2')\ x_2$$

Solving for x_2 in terms of x_1 we find

$$x_2(t) = x_1(t) + m_1 \int_0^t e^{-m_2(t - s)} \sin m_3(t - m_4 - s)\ x_1(s)\ ds$$

in which m_1, m_2, m_3, and m_4 are functions of the constants of seismograph and building, and are all real. (This form is dependent on the inequality of r_2 and r_2', but many of the results for $r_2 = r_2'$ may be obtained as limits from this equation. In the cases $r_1 = r_1' = 0$ and $r_2 \doteq r_2' \doteq 0$ we have the solution of the seismometer-equation and an approximate solution of the inverse problem. The solution of the latter problem may be obtained from the seismometer-equation by double integration, but the present method is also useful.)

The same equation holds for the error δx_1 and the resulting error δx_2 in the building motion. The upper bound of $|\delta x_2|$ for the most unfavorable buildings and earthquakes is our measure of the error. Denoting by b an upper bound for $|\delta x_1|$, we find by inspection an error-function which maximizes $|\delta x_2|$; it is a function which is everywhere equal to +b or -b and whose sign agrees with that of $\sin m_3(t - m_4 - s)$ except at time t, when it agrees with that of m_1, or the negative of such a function. We expand this function in Fourier series; the integral may be evaluated term by term although the Fourier series does not converge uniformly. In the unfavorable case of a long-continued earthquake and a feebly damped building the first term predominates, and in the limit becomes infinite in comparison to the other terms, so that the study of this term suffices for the purpose of estimating the maximum error due to any error-function δx_1.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SEISMOGRAPHIC TILT-MEASUREMENTS AT BUFFALO

John P. Delaney

(Abstract)

With instrumental arrangement as previously described at the Pittsburgh and Ottawa meetings, together with additional data from thermograph, barograph, and spirit-level, three distinct types of ground-tilting have been found. Tilting in one direction only has been studied, along a northeast-southwest line, because this is the only direction of noticed tilt on the Wiechert pendulum.

The first type of tilt is irregular, a few tenths of a second of arc and of duration five to 20 hours. The tilt appears related to changes in the barometer rather than in temperature, and probably it is caused by steep barometric gradients when these occur along the line of orientation of the instruments.

The second type of tilting has an annual period, amounting to about three seconds of arc southwesterly in spring and summer and northeasterly in fall and winter. This annual tilt appears deep-seated in the rock foundation of the pier, since temperature-changes, either in the vault or in outside weather, seem to cause no immediate tilting.

The third type of level-change appears to be a constant southwesterly tilt affecting both the Wiechert and Wood-Anderson seismometers. Displacement of the Wood-Anderson zero-position between January-February 1935 and the same months in 1936 indicates a tilt-accumulation in the course of the year of approximately 0.7 second of arc. Further spirit-level data will be required for confirmation and measurement of this tilt, and for study of its persistence.

Canisius College,
Buffalo, New York

LOCAL EARTHQUAKES IN NEW ENGLAND, 1934-1935

Mary P. Collins

(Abstract)

During 1934 and 1935, records of approximately 150 disturbances, definitely local in character, were obtained on the Benioff seismographs at the Harvard Seismograph-Station. Distances for 105 of these shocks were computed from the S-P interval, using the Harvard travel-times for New England. The range of distances varies from 12 to 320 km, with a total of 60 shocks between 100 and 150 km from the station.

An attempt to establish criteria for distinguishing blast-records from those of local earthquakes is discussed. It is concluded that most of the records investigated represent natural earthquakes, in spite of a curious concentration in daytime hours.

Seismograph-Station,
Harvard University,
Cambridge, Massachusetts

THE NEW SEISMIC VAULT AT FORDHAM

J. Joseph Lynch

(Abstract)

The William K. Spain Seismic Station of Fordham University was moved from its former position on the campus to the site it now occupies, adjacent to the Physics Building, Freeman Hall. A diagram was shown to demonstrate the set-up of the piers, six in number, with the center pier, a semicircular one, enabling the adjustments of instruments from either side with greater ease. The new waterproofing cement was described, as well as the dehumidifying unit which has been giving excellent results since its installation.

Fordham University,
New York, New York

CORRELATIONS BETWEEN TILTING OF THE GROUND AND THE TIDES IN CHESAPEAKE BAY

George Merritt

The interferometric tiltmeter, described in greater detail in previous issues of the Transactions, consists of a shallow basin containing a liquid, and a flat glass cover-plate on which is engraved the reference-marks. The surfaces from which the interfering reflections are obtained are the upper surface of the liquid, which remains level, and the lower surface of the cover plate, which tilts with its support. These surfaces are set about 4 mm apart. For visual observation a simple combined illuminating and viewing instrument is used but for purposes of study it seemed desirable that a recording device be attached.

The recorder (Fig. 1) was developed and tested under a grant of the National Research Council. Several experimental machines were made and the most successful one produced so far has been sent to the University of California where a tiltmeter-station is maintained in cooperation with the Seismological Section of the United States Coast and Geodetic Survey.

The recording apparatus consists essentially of a camera, substituted for the eyepiece of

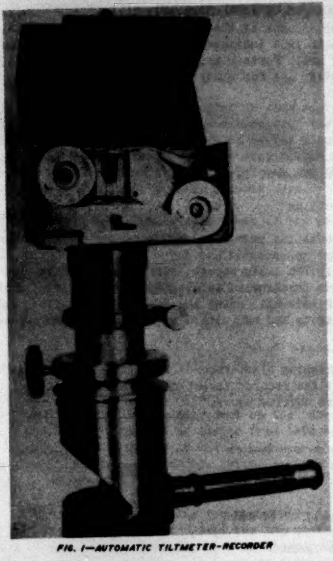


FIG. 1—AUTOMATIC TILTMETER-RECORDER

the illuminating and viewing instrument. This camera uses 32-mm supersensitive panchromatic perforated moving-picture films. With these films an exposure of 10 to 15 seconds has been found sufficient to obtain good pictures of the fringe-system formed by the yellow emission of helium. One week's record (hourly pictures of the fringes) consists of a strip of film 10 to 12 feet long, which is easily filed and provides a permanent record for future study. The film may be examined by projecting it, one frame at a time, on the wall at a magnification of about 30X or 40X.

Power for winding the film and operating the shutter is provided by a weight suspended from a cable wound on a drum. The timing mechanism is a double-spring power-drive clock operating a cam which makes and breaks an electric circuit. The electrical power is furnished by a six-volt storage-battery, its function being to light the helium tube used as a light source and to operate a solenoid which releases a trigger, allowing the suspended weight to operate. A yellow filter is introduced which suppresses the other emissions of the helium lamp so that the yellow fringes are clear and sharp. A side-entry telescope is provided to enable the operator to inspect the fringes without disturbing the camera or opening the shutter.

While operating the recorder at Cove Point Landing on the Chesapeake Bay, a tide-gage was installed and maintained by the United States Coast and Geodetic Survey for a period of two months. This was situated in seven feet of water, opposite to the tiltmeter, about 50 yards from shore and about 200 yards from the tiltmeter, which is on the first high ground.

A correlation between tide-load and tilt was found to be small but positive. The simple formula $r = \sum XY/n\, S_x\, S_y$ was used. In this formula $S_x = \sqrt{\sum X^2/n}$, $S_y = \sqrt{\sum Y^2/n}$, X and Y are the deviations from the mean of the tilt and tide, respectively, and n is the number of pairs used. The value $r = 0.17 \pm 0.06$ was found, using 514 pairs of observations.

Since barometric pressure, temperature, and ground-water probably also introduced tilts it is not to be expected that a very large correlation would be found. The softness of the strata (the tiltmeter is set in blue clay) may also lessen the amount of observable effect. On the other hand, the situation is favorable in that the tide phase is such that the loading effect is not greatly masked by the tide-producing forces.

A record of the barometric pressure was kept by means of a barograph furnished by the United States Weather Bureau but so far no correlation has been found between any component of the tilt and the pressure.

U. S. Coast and Geodetic Survey,
Washington, D. C.

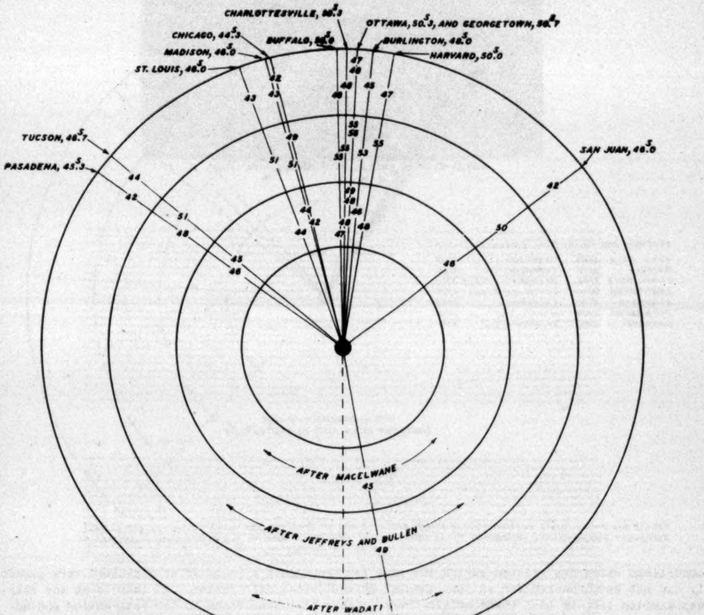
A DISCUSSION OF SOME PROBLEMS IN EPICENTER WORK

R. R. Bodle

During the past year a number of seismological questions have presented themselves. I will discuss three of them very briefly here. The first has to do with the problem of regional variation in the travel-time of seismic waves. An unusual example of this situation has been found, namely, the shock of November 30, 1935, in the Caribbean Sea near Panama (see Fig. 1). The epicenter in this case was adopted as 10°1 north latitude and 79°5 west longitude. The distance from this point to each of the recording stations was then computed, using a formula for great-circle distances without correction for the figure of the Earth. These distances were then used to take out the (P-O) values from three different sets of well-known seismological tables. The (P-O) values were then subtracted from the arrival-time of the first wave at each station. The results in seconds may be seen in Figure 1. Each station is here indicated by an approximate direction-line from the epicenter. At the outer end of each direction-line is found the name of the recording station and the mean value of origin in seconds as determined from the three sets of tables. Note that these mean times for the group of stations from Buffalo to Harvard are about four seconds later than any of the other mean times of origin. This indicates that the travel-time of the preliminary earthquake-waves to the stations in this sector was slower by four seconds.

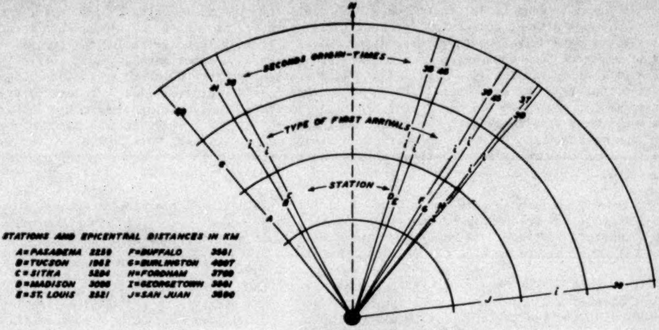
This one example suggested the making of further examinations of a similar nature. Because of the difficulties frequently encountered in making locations of the shocks along the west coast of Mexico, it seemed desirable to treat some of them with this method of analysis. So far it has been possible to examine two of these shocks.

Figure 2 shows the result for the shock of May 8, 1933, in the State of Guererro. The data were not plentiful but were of a positive nature with first arrivals as indicated by the letter e for emergent and the letter i for impulsive type. Note that the time of origin at station J is in the same range as the origin-times for stations A, B, and C. The range in times of origin at the remaining stations is much larger--37 to 46 seconds. Under the high standard of operating



CHARLOTTESVILLE, 50.3
OTTAWA, 50.3, AND GEORGETOWN, 50.7
CHICAGO, 44.3
BUFFALO, 50.0
BURLINGTON, 46.0
MADISON, 46.0
HARVARD, 50.0
ST. LOUIS, 46.0
TUCSON, 46.7
PASADENA, 45.3
SAN JUAN, 46.0
AFTER MACELWANE
AFTER JEFFREYS AND BULLEN
AFTER WADATI
HUANCAYO, 45.7
S

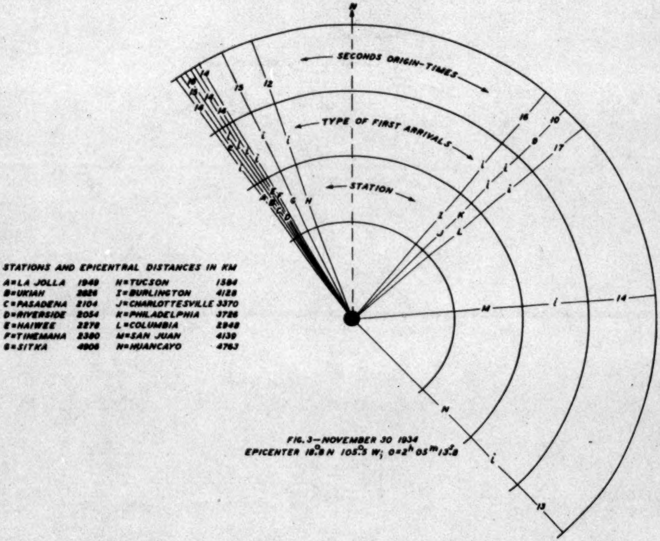
FIG. 1—SHOCK OF NOVEMBER 30, 1935; EPICENTER 10°.[illegible] N, 79°.3 W; MEAN ORIGIN-TIME, O = $3^h\ 39^m\ 48^s$
DIAGRAM SHOWING (a) STATION, (b) STATION-DIRECTIONS, AND (c) SECONDS OF ORIGIN-TIMES
BY (P-O)-VALUES AFTER TABLES OF MACELWANE, JEFFREYS AND BULLEN, AND WADATI


N
SECONDS ORIGIN-TIMES
TYPE OF FIRST ARRIVALS
STATION
40
41
39
39
40
39
40
37
39
39
i
e
A
B
C
D
E
F
G
H
I
J

STATIONS AND EPICENTRAL DISTANCES IN KM

A=PASADENA	2259	F=BUFFALO	3561
B=TUCSON	1962	G=BURLINGTON	4007
C=SITKA	3284	H=FORDHAM	3709
D=MADISON	3096	I=GEORGETOWN	3861
E=ST. LOUIS	2521	J=SAN JUAN	3890

FIG. 2—MAY 8 1933
EPICENTER 17.0° N, 101.0° W; O=10h 33m 42.2s


N
SECONDS ORIGIN-TIMES
TYPE OF FIRST ARRIVALS
STATION
14
15
12
16
10
17
14
13
i
e
A
B
C
D
E
F
G
H
I
J
K
L
M
N

STATIONS AND EPICENTRAL DISTANCES IN KM

A=LA JOLLA	1949	H=TUCSON	1584
B=UKIAH	2826	I=BURLINGTON	4128
C=PASADENA	2104	J=CHARLOTTESVILLE	3370
D=RIVERSIDE	2054	K=PHILADELPHIA	3726
E=HAIWEE	2278	L=COLUMBIA	2948
F=TINEMAHA	2380	M=SAN JUAN	4139
G=SITKA	4906	N=HUANCAYO	4763

FIG. 3—NOVEMBER 30 1934
EPICENTER 18.8° N 105.5° W; O=2h 05m 13.8s

FIGS. 2 AND 3—DIAGRAMS SHOWING (a) STATIONS, (b) ORIGIN-TIMES BY (P-O)-VALUES USING COMPUTED EPICENTRAL DISTANCES AND ARRANGED ACCORDING TO AZIMUTH, AND (c) TYPE FIRST ARRIVAL — e=EMERGENT, i=IMPULSIVE

conditions which has existed during the past few years such a range in origin-times very probably can not be accounted for as instrumental or accidental differences. If this is so the only explanation left is that these origin-times picture real conditions in the retardation and acceleration of the travel-times of seismic waves.

A like examination was made for the shock of November 30, 1934, in the region of Colima, Mexico. Note from Figure 3 that the range in origin-times for the stations to the northeast is similar to the ranges shown in Figure 2. Were it not for the definite indication of regional variation shown in Figure 1 one would be inclined to overlook the situation shown in Figures 2

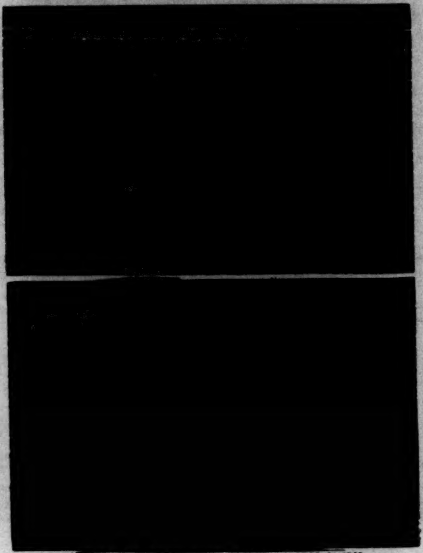


FIG. 4—SEISMOGRAM, SITKA, ALASKA, OCTOBER 31, 1935

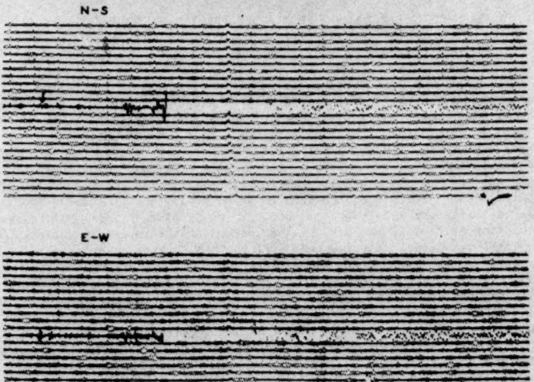


FIG. 5—SEISMOGRAM, SITKA, ALASKA, OCTOBER 18, 1935

and 3. In all three cases, however, there are rather definite indications that the transmission of seismic waves from the Mexico-Central America Region to stations in the eastern half of the United States is irregular in nature. Future studies may possibly bring forth the reason.

The second problem considered has to do with the Attica, New York, shock of August 12, 1929. Was it deep focus in nature? It seemed possible that this might be so in view of the 200-kilometer depth assigned to the Temiskiming shock of November 1, 1935. After computing the distances to the various stations reporting, the data were plotted and compared with the travel-time charts for several depths. There was no indication that this shock was other than normal in nature.

The last point has to do with the recording of the Montana shocks of October 18 and 31, 1935, at Sitka, Alaska.

Figure 4 shows the record at Sitka for the shock of October 31, 1935. The amplitude of the P-phase on both components is to be noted. The azimuth of this shock from Sitka was about 118° from north. The amplitudes of the P-phases indicated an azimuth approximately 130° from north--a quite reasonable agreement considering the possible effect of the microseisms on such a determination. Note the character of the microseisms.

In Figure 5 the amplitude of the microseisms is larger and may perhaps account for the unusual situation which we find. The P-phase on the north-south component is not recorded at all unless it is evidenced by one slight irregularity in the microseisms. Is this a correct picture? If it is correct and if the recording has not been influenced by microseisms, there must be considerably more to learn about the transmission of seismic waves. So far the writer has been unable to find any indication of malperformance of the instruments. Daily damping-tests appear on the records for both days and the apparent satisfactory registration of the microseisms seems to indicate that the equipment was operating properly. In addition the decay-tests run off October 8 indicated that the equipment was in proper order. One example such as this is not sufficient to prove the case but it would seem to indicate that azimuth-determinations from a single station may be seriously impaired by the effect of microseisms.

U. S. Coast and Geodetic Survey,
Washington, D. C.

DEEP-FOCUS EARTHQUAKES FROM A GEOLOGIST'S POINT OF VIEW

W. T. Thom, Jr.

Thanks to the recent work of the seismologists, it is evident that the time is ripe for further major advances along what Father Macelwane has termed "the geologico-seismological frontier" [see 1 of "References" at end of paper], and it therefore seems appropriate that students of structural geology should so far as possible actively contribute toward current and future collaborative study -- both as to how the Earth's crustal, subcrustal, and nuclear portions are constituted, and as to the nature of the dynamic processes which characterize and control the recurrent crustal and subcrustal deformative movements. To the writer, it appears that the most immediate and important direction in which geologists can assist in seismological-geological research lies along the line of cooperative study of deep-focus earthquakes, the discovery of which by the seismologists has opened an exceedingly interesting new chapter in earth science. The writer's endeavor, consequently, will be both to mention certain time, space, and dynamic relationships which may multiply and qualify the multiple working of hypotheses now being used in the study of the origin and tectonic significance of deep-focus earthquakes, and to mention certain matters of current experience which may suggest how and why deep-focus earthquakes occur. Because much more information obviously must be had before anyone can demonstrate that he has the correct answers as to how and why earth deformation takes place, a large proportion of the paragraphs to follow will consist merely of summary statements of personal opinion, the details and derivation of which will be given only as and if the views expressed prove to be sufficiently interesting to bring forth inquiry or discussion.

When it first became fairly well established that major earthquakes can and do originate at depths of several hundred kilometers, the questions at once arose as to how such postulated occurrences could be reconciled with current ideas as to how isostatic readjustments of crustal balance take place [2]; and as to the relative rôles being played by tangential thrust and (vertical) isostatic movement in those regions featured both by recent active mountain-building, and by present-day earthquakes of great focal depth. Furthermore, there naturally became manifest a tendency in some quarters to assume that "isostasy was disproved" by the indicated origination of earthquakes at great focal depths, and it is on this point that an opinion will first be expressed.

Even omitting all geodetic evidence, the geologic information in hand tends very convincingly to support the idea that isostatic readjustments have occurred, and are still occurring in some manner -- doubtless quickly and at a definite depth -- in regions underlain by thin, blister-like, bodies of molten rock; somewhat less quickly, and by a distributed movement (flow by recrystallization), in regions underlain by highly heated, but unmelted rocks; and slowly and spasmodically by multiple shears (as in a dry glacier) in regions underlain by relatively cold subcrustal rocks [3]. Combining the geodetic and geologic evidence, it seems particularly clear that the general concepts as to the existence and reestablishment of some form of isostatic equilibrium of the Earth's crust cannot yet be lightly discarded by students of earth mechanics.

Assuming that some form of "isostasy" is to be taken as a cardinal working hypothesis, what relations do the vertical motions incident to isostatic adjustment bear to the tangential thrusts which predominate in the original production of mountain-systems? The evidence indicates that isostatic readjustment tends to take place very slowly and more or less continuously, whereas mountain-building movements, under tangential thrust, seem to occur relatively much more suddenly, and in a series of major rhythms or cycles, modified by rhythmic subcycles of at least second and third orders of magnitude. Present evidence, also, indicates that the primary, linear, mountain-systems produced by tangential thrust are commonly more or less modified and multiplied by secondary mountain-folding, resulting from "landslide" movements in geosynclinal areas. During these "landslides" great sedimentary sheets or prisms become tilted beyond their angles of repose, due to deepening of geosynclines, and glide off toward the geosynclinal axis with consequent folding, crumpling, and thrusting -- as has demonstrably occurred in the Bearpaw-Highwood Region of Montana [4, 5], and as has apparently occurred in the Alps and elsewhere.

In summary then, so well as one may judge from present evidence, the geologic record suggests that, due to a more or less continuously and progressively developing lack of adjustment between the Earth's crustal area and volume, elastically-stored tangential compression recurrently mounts within the crustal rocks until the strength of the crust is first approached and then exceeded -- attended first by the accelerated development of geosynclines, and then by crustal rupture, with consequent thrusting and folding of the geosynclinal rocks into mountain-ranges -- events which characteristically mark the culmination of orogenic episodes. During the period of gradual stress-accumulation the Earth apparently tends (very slightly) to approach a tetrahedral form, with slight emergence of the continental shields marking the corners of the "tetrahedron"; whereas, during the shorter periods of orogenic stress-release, the Earth again tends to return relatively rapidly to a more nearly spheroidal form.

However, even granting that deformation under tangential compression is manifestly effective to depths of tens of kilometers, and even if "isostatic" compensatory movements apparently extend to considerably greater depths, the question yet remains as to whether we must not appeal to other causes than those involved in orogeny and isostasy to provide the large amounts of energy, locally released, which give rise to deep-focus earthquakes. For example, may not these energy-releases be due to chemical or physical transformations, rather than to more immediately dynamic causes [6]? Present opinion seems to be that there is little probability that all or most of the deep-focus earthquakes may be due to "explosions" consequent upon the subsidence of mineral substances to depths and pressures beyond their zone of stability; and a somewhat greater possibility that either an irregular heating and cooling may be responsible [7], or that sudden physical inversions -- attended by volume changes, possibly with gas evolution -- may occur suddenly at great depth, as it evidently did occur at shallow depth at the time of the recent Lassen Peak eruptions.

Happenings which are possibly more suggestive of how deep-focus quakes originate are, perhaps, afforded either by the gas "outbursts" occurring in coal and salt mines (which have been described in the Transactions of the American Institute of Mining Engineers); by the gas-eruptions and mud-volcanoes of various oil-field regions; or by crypto-volcanic and related structural features.

In the case of known mine "gas-outbursts", gas under heavy pressure apparently occurs adsorbed upon, or occluded in coal or salt. Residual tectonic stresses are latent in parts of the bed mined, and consequently when mining activities "trip the trigger", crushing of the bed begins with accelerating liberation of compressed gas from the large surface-area exposed by crushing, producing in turn a further accelerated crushing of more of the host-rock, so that, until the local residual stress is relieved, great quantities of gas and comminuted coal (or salt) are explosively discharged during a brief period of time, often causing serious loss of life as well as of property.

In the great mud-volcanoes of the Caspian region, it has been reported, natural gases, occurring at depths of some miles, recurrently have accumulated pressures sufficient to blow out the water and mud filling the throats of the vents, thus, at times, giving rise to quite violent, explosive eruptions. A comparable phenomenon has also been observed at Seneca Lake, New York [8], where natural gas, occurring under high pressure in a nearby gas-field, has escaped into the thick glacial deposits filling the bed of the Lake, until these deposits were repeatedly so saturated with compressed gas that the slight reduction in pressure produced by the passage of a barometric "low" over the Lake "touched off" sudden and violent gas-eruptions. Similar sudden outbursts of gases or vapors of much deeper origin evidently must also have been responsible for the production of some, if not all, of the "cryptovolcanic" structures studied in Europe and North America, and of the "outbursts" which were productive of the diamond pipes of South Africa which, it has been estimated, must have come from depths of at least 70 km, if not more. The possibility that gases, slowly accumulated and suddenly released, can be responsible for the production of at least some deep-focus earthquakes is, therefore, suggested for what it may be worth.

The more probable cause of most deep-seated earthquakes is, however, apparently to be sought in the operation of that set of tectonic conditions which the writer is accustomed to describe as characteristic of "basin mechanics". It is a matter of common knowledge among geologists that, when areas of flat-lying bedded rocks are warped into the form of a basin or trough, a gliding tends to occur on each bedding plane in the warped series above its neutral surface -- the peripheral portions of each bed within the basin tending to glide laterally toward the basin-margins over the surface of the bed next beneath -- whereas, beneath the neutral surface of the deformed series nearly vertical tension cracks develop, with a tendency toward a progressively greater gaping toward the bottom. It is equally true, though as yet apparently generally either not understood or appreciated, that, if a flat-lying layer of massive crystalline rocks ten or a hundred or a thousand kilometers thick, is similarly and rapidly warped into a basin or trough form, such warping can occur only if ruptures occur above the neutral surface of the deformed mass, permitting of similar glidings, and if actual or potential tensional cracking occurs below that neutral surface. Such vertical cracks or planes of lowered strength and pressure quite conceivably provide the channels whereby the basic intrusions and lava-flows of geosynclinal zones approach or reach the surface; and whereby the materials composing the diamond "pipes", and the Great Dike of South Africa, have risen from relatively great depths.

It seems highly significant that the deep-focus earthquakes thus far reported have not, for the most part, occurred in regions where rapid, shallow mountain-folding is progressing, but, rather, beneath nearby regions of greater crustal strength, within which rapid basin- or trough-development may be incipient. Most deep-focus earthquakes thus far known have been reported from regions bordering the Himalayan, Andean, East Indian, and Japanese orogenic belts, though an important exception (if not the exception) to this rule has been provided by the deep-focus quake which recently occurred near Timiskaming, Ontario, in the heart of the stable Canadian Shield area. This area, characterized both by great structural competence and by low temperature-gradients (that is, by relatively very cold -- and hence strong -- subjacent rocks) is one which is undergoing rapid readjustments in consequence of the recent disappearance of the last great ice sheet.

In summary, then, the following suggestions are offered regarding several possible modes of origin of deep-focus earthquakes:

(1) They may conceivably be due, at least in part, to "explosive chemical inversions at great depth.
(2) They may be due to sudden changes in physical state productive of important volume increases or decreases.
(3) They may be due to slow gas-accumulation followed by sudden gas-eruption.
(4) More probably they are either due to deep tension development along (potential or actual) vertical fissures, or to the development of curved rupture surfaces at less depth, as consequences of the rapid development of basin- or trough-structure in cold, strong rocks, contiguous to the mobile orogenic belts in which rapid deformational movement at shallow depth is now mainly concentrated.

The main factors involved are necessarily the chemical and physical make-up of certain crustal and subcrustal rock-bodies, their forms and mechanical arrangements, their temperatures, the ways in which they are stressed and, above all, the rapidity and irregularity with which stresses are being applied, either by mountain-building movements and processes or otherwise.

Much more remains to be done before we can devise what Father Stechschulte [2] has termed "a complete theory of the Earth's interior, and of its structure, constitution and development", but the writer shares the belief held by many, that by geophysical (and mainly seismic) progression from the geologically known surface to the geologically unknown depths of the Earth, cooperative effort can speedily provide us with far better ideas as to why and how deep-focus earthquakes occur and as to what they signify in terms of the composition and dynamic behavior of our planet.

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A MECHANICAL METHOD OF ANALYZING ACCELEROGRAMS

Frank Neumann

In seismological research, particularly that branch relating to engineering studies and vibration-work, one of the most important practical problems is that of computing the motion of a pendulum when the ground-motion is known. When it is realized that the same formula is also used to estimate the response of engineering structures to earth-movements, its importance is even more apparent. The problem is the reverse of that with which seismologists are ordinarily familiar, namely, that of computing the ground-motion when the pendulum-motion is known from seismographic records. In all computations of this character the assumption of simple harmonic motion makes either phase of the problem quite simple if only rough approximations are desired, but seismological research as applied to engineering problems has imposed new standards on the seismologist and he is faced with many practical problems which heretofore held only theoretical status. As it is now necessary to compute the complete response of a vibrating structure, the assumption of simple harmonic motion no longer suffices and he is confronted with equations which for practical application are so complex that the problems involving them seem almost hopeless of solution.

The equation of motion of a damped pendulum when subject to forced vibration at its point of support is

$$\ddot{y} + 2ky + p^2y = \ddot{x}$$

in which x is the instantaneous displacement of the support, y is the instantaneous displacement of the center of oscillation of the pendulum relative to the moving support, k is a damping factor in which damping is assumed proportion to velocity, and p is a factor involving the pendulum-period. If the motion of the support, x, is known, the solution for instantaneous values of the pendulum-displacement is given by the equation

$$y = (1/u)\int_0^t e^{-k(t - \eta)} \sin \mu \, (t - \eta) \; F(\eta) \, d\eta$$

in which $u = (p^2 - k^2)^{1/2}$. This is the equation which must be applied hundreds of times to compute the motion of a vibrating system for a relatively short period of time.

In giving thought to the possibility of using mechanical methods as a solution to the problem, a number seem quite plausible from a theoretical viewpoint. The simplest and evidently most practical method is that involving principles of the simple torsion-pendulum when the ground-motion is given in terms of acceleration. Fortunately acceleration is the easiest of the elements of motion to measure in the case of an earthquake, and accelerometers far outnumber any other type of seismometer in operation by the United States Coast and Geodetic Survey. The underlying principle of the "torsion-pendulum analyzer" is based on the fact that if the torsion-head is turned through angles which are proportional to the instantaneous values of acceleration (as recorded on an accelerogram), the mass of the torsion-pendulum will respond, in angular dis-

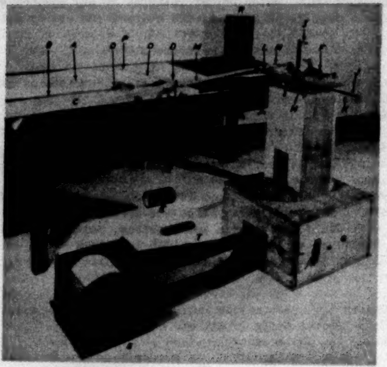

FIG. 1—GENERAL VIEW OF THE TORSION-PENDULUM ANALYZER

Legend for Figure 1

A = aluminum plate for mounting enlarged tracing of original acceleration-curve
B = narrow strip of hard wood fixed to upper edge of A accurately parallel to zero-line of acceleration-curve
C = wide board clamped rigidly to table--upper edge of B slides along a smooth edge of C
D = two gravity-clamps to keep B snugly against edge of C, each clamp consisting of a short strip of wood which presses B against C; short strip is fixed with respect to C except that it is free to move normal to strip and board; another short strip of wood is nailed to top of it to form the stem of a "T" which is restrained in all but longitudinal motion by suitable blocking on C; a pull is exerted on lower end of each "T" by a string attached to a heavy weight; if A is pulled away from C, the pull of the weight is sufficient to force it back, thus keeping the zero-line of acceleration-curve exactly equidistant from sliding surfaces at point of curve being traced
E = 15-pound lead weight operating clamps D D
F = winch used to pull A across the table--this cord is attached to end of B and pulls against restraining forces of D D
G = box enclosing torsion-pendulum
H = torsion-head of the pendulum--only partly visible
I = spring-device tp reduce friction in torsion-head by exerting vertical pull
J = rod sliding longitudinally in two sleeve-supports
K = cord attached to J and wound one or two times around H
L = universal joint connecting J with rest of lever-system controlling sensitivity of apparatus
M = lever-arm pivoted at N and connected with J at L
N = pivot-point of M
O = lever-arm pivoted on M at Q, and carrying tracing pointer P at free end; O always moves parallel to J--any slight variation which may enter due to lack of uniform motion of A is negligible
P and Q = pointer and pivot (see O)
R = metronome
S and T = recording apparatus and light-trap T for daytime recording

placement, in a manner identical with that of any other vibrating system having the same period and damping as the torsion-pendulum. It is simply another way of applying acceleration to the support of a pendulum other than by translation of the support, or tilting of the axis of rotation in the case of a horizontal pendulum. The torque in the wire of the torsion-pendulum is equivalent to applying a field of force to the mass of the pendulum, just as tilting a horizontal pendulum furnishes a means of applying a portion of the Earth's gravitational field of force to the pendulum.

The outstanding advantage of the torsion-pendulum lies in the fact that all the motions involved may be slowed up greatly without changing the nature of the response-curve, provided the

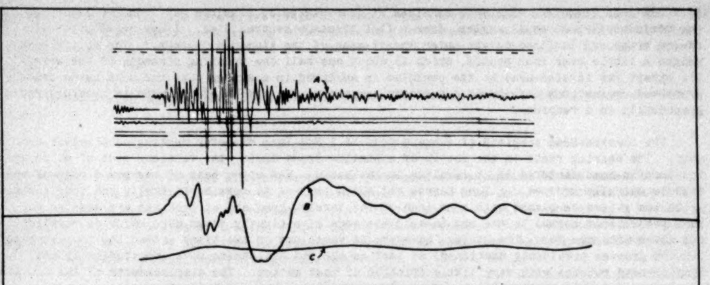

FIG. 2—ACCELEROGRAPH-RECORD OF HELENA (MONTANA) EARTHQUAKE, OCTOBER 31, 1935
(A=PORTION OF RECORD; B=RESPONSE-CURVE OF ANALYZER, EQUIVALENT TO RECORD OF A 5-SECOND PENDULUM MAGNIFYING 4 TIMES; C=CURVE SHOWING STABILITY OF ZERO-POSITION OF TORSION-PENDULUM WHILE IN OPERATION)

speed at which the acceleration is applied and the period of the torsion-pendulum are both slowed up in the same ratio. As torsion-pendulum periods can be made very long without great difficulty, it is possible to apply any observed accelerations to the torsion-head of the pendulum manually, thus doing away with all of the apparatus necessary to reproduce earthquake-motions on true time-scale. It is this characteristic of the torsion-pendulum analyzer which appears to place it above other types in point of practicability. Moreover, it has a sensitivity-characteristic which is ideal. There is almost no limit, in practical work, to the scale of the response-curve. Another advantage is the simplicity of the method of determining instrumental constants. The weakest spot in the apparatus lies in mechanical imperfection, which is not serious, and the instability of long-period torsion-pendulums due to convection-currents and other external causes, all of which can undoubtedly be overcome.

The experimental apparatus (Fig. 1) at the United States Coast and Geodetic Survey has been made in rather crude fashion, and very little work has been done with it, but enough has been accomplished to establish the practicability of the idea. The aim in its design was to reproduce a curve corresponding to that which would be obtained from a 10-second displacement-meter pendulum. Because of lack of time, and another reason to be stated later, the response of a 5-second pendulum was obtained using an acceleration-curve of the Montana earthquake of October 31, 1935. In Figure 2, the portion of the accelerograph-record used is shown at A, the response of the torsion-pendulum at B, and the curve showing the stability of the pendulum on the zero-line at C. Each dash represents a half-second time-interval. In the first attempt at applying acceleration in the form of torsional displacements of the torsion-head, the pendulum-period was slowed up to one-twentieth of the speed of the accelerograph at the time of the earthquake, requiring a torsion-pendulum period of 200 seconds, that is, 20 X 10. This was entirely too fast to follow the acceleration-curve manually with fidelity. It was found necessary to slow up the rate 100 times, thus requiring a pendulum period of 1000 seconds or about 17 minutes. The record shown was made with the pendulum operating at that period and damped magnetically to a ratio of about 8 to 1. However, as the sensitivity or scale of the response-curve decreases as the square of the speed at which the acceleration is applied to the torsion-head, and as it was desired to increase the scale of the response-curve (above unity) because of a certain amount of instability in the zero-line of the apparatus, the accelerations were actually applied at 1/200 normal speed, so that the response was equivalent to that of a 5-second pendulum, with magnification of four instead of unity. In the major characteristics of waves of 5-second period and less, the record checks with the displacement-curve computed by double-integrating the same acceleration-curve, but the presence of a long-period wave (of the order of one minute) on the computed curve makes critical comparison difficult. The response-curve of the analyzer represents the response of a 5-second pendulum and should not be expected to show such a long wave except with greatly reduced amplitude. There is strong evidence that it is present.

A measure of the stability of the zero-line of the apparatus was obtained by tracing over the approximate zero-line of the acceleration-curve at the same rate of speed at which the acceleration was applied to the torsion-head. The response of the pendulum is shown on the illustration at C of Figure 1.

The suspension of the experimental torsion-pendulum is a 30-inch length of steel piano-wire of 0.005-inch diameter. The mass consists of four pieces of aluminum rod 7 inches long projecting horizontally, at equal angles, from a flat aluminum central disc. A one-pound piece of square brass rod is fixed to the outer end of each of the aluminum "spokes." The entire mass weighs a little over four pounds, which is about one-half the breaking strength of the wire. All except the torsion-head of the pendulum is enclosed in a wooden box, the mass being crudely protected against the effects of convection-currents. The motion of the mass is recorded photographically on a recorder.

The torsion-head consists of a brass disc of 1 3/4-inch diameter resting on a roller-bearing unit. The bearing rests in the bottom of a shallow brass basin, the vertical side of which keeps the torsion-head centered as it revolves in the basin. The upper half of the round edge of the disc is spirally grooved. A long narrow rod which is free to move horizontally and longitudinally in two guides is placed within an inch of the torsion-head and at each end are mounted one-inch projections normal to the rod to hold the ends of a tightly drawn cord which is parallel to and moves with the rod. The string, however, is wound one or two times around the torsion-head (in the grooves previously mentioned) so that as the rod and string move longitudinally the torsion-head rotates with very little friction or lost motion. The displacements of the rod are proportional to the instantaneous values of acceleration, the rod being actuated by a lever-system which has at its other end a pointer that is moved manually over the acceleration-curve. As it is necessary that the pointer have only one degree of freedom, the accelerograph-curve must be moved beneath it. This is done by hand, the motion of the aluminum plate on which the curve is mounted being restrained by a pair of gravity-clamps through which a long strip of wood attached rigidly to the top edge of the plate is forced to slide. The strip of wood is, of course, fixed accurately parallel to the zero-line of the curve.

In practice it was found desirable to first place marks on the acceleration-curve at equal time-intervals. In operating the pointer manually one of these marks was passed over at every tick of a nearby metronome.

In practice the fundamental theoretical consideration is: What must the sensitivity of the torsion-pendulum be, in terms of angular deflection of the torsion-head per unit of acceleration, to obtain an equivalent pendulum-response of unit-magnification or some arbitrary magnification? The relation between the various elements involved may be found in a rather simple way by referring first to the ordinary magnification-curve of a damped pendulum for sustained simple harmonic motion which is based on the following equation in which T_o is the pendulum-period, T_e is the impressed period, and h is the damping factor.

$$V = 1/\left\{[(T_e^2/T_o^2) + 1]^2 + 4(T_e^2/T_o^2)(h^2 - 1)\right\}^{1/2}$$

From this curve it is a well-known fact that a seismograph pendulum with no lever-magnification records practically true displacement for impressed periods which are considerably less than the pendulum-period. If a curve representing the corresponding accelerations is drawn, it represents the sensitivity of the seismograph-pendulum to the equivalent periodic accelerations. For impressed periods which are long relative to the pendulum-period it is well known that the sensitivity of the seismograph to acceleration is constant, and the seismograph is in effect an accelerometer. In the theory of the torsion-pendulum analyzer, however, interest is restricted to the short-period end of the acceleration-curve where the seismograph is functioning as a displacement-meter, and here the equation of the acceleration-curve is practically equivalent to (T_e^2/T_o^2). This means that if periodic accelerations are impressed on the support of a seismograph-pendulum, or on a torsion-pendulum by rotational displacement (of arbitrary magnitude) of the torsion-head, the displacement of the pendulum with respect to the applied periodic acceleration will be in the ratio of T_e^2 to T_o^2. Therefore, if the torsion-head of a torsion-pendulum is given periodic angular motion through an angle θ, which is arbitrarily made equivalent to unit-acceleration, the angular displacement of the pendulum-mass will be (T_e^2/T_o^2) which will be called θ'. If x is the displacement of the light-spot on the recording apparatus which is registering the motion of the torsion-pendulum and L is the distance from pendulum-mirror to recorder, then from the above relations, θ' equals $x/2L$ and

$$x = 2L\, T_e^2\theta/T_o^2$$

It is known that from the equation $a = 4\pi^2 A/T_e^2$, when acceleration is unity

$$A = T_e^2/4\pi^2$$

Therefore, the magnification of the response-curve obtained from the torsion-pendulum is

$$V = x/A = 8\pi^2 L\theta/T_o^2$$

As the angle θ is capable of a great range of values, and is altogether arbitrary, a great range of sensitivity is possible, depending in practice on the mechanical levers used in transmitting the acceleration to the torsion-head, the diameter of which can also be varied through a great range.

The following equation was used for the particular set-up of the torsion-pendulum under discussion

$$V = (8\pi^2 Ld_1/r)(d_2t/T_{oT}d_3)^2$$

in which d_1 = circumferential displacement of torsion-head corresponding to one cm/sec^2; r = radius of torsion-head; T_{oT} = period of torsion-pendulum; t = time-interval between metronome-beats; d_2 = length (in cm) of a one-second time-interval on the magnified trace; d_3 = horizontal distance (in cm) traveled by tracing stylus during one metronome-beat; L = distance from mirror to recording drum; T_o = period of hypothetical pendulum or equivalent seismograph-pendulum; and $T_{oT}/T_o = d_2t/d_3$ = pendulum-period magnification.

In the experiment the curve used was an accurately drawn tracing about 7.5 times larger than the original accelerogram.

It may be said that the use of the torsion-pendulum in the manner described opens up a new avenue of research in seismological problems. If successful in practice it would seem to eliminate the need for all types of instruments other than accelerometers where quantitative results are of paramount importance. This would include displacement-meters and multi-pendulum analyzers.

The idea might be applied to the design of seismographs outside the ordinary range of periods, especially ultra-long periods, and to seismographs in which moderately long pendulum-periods are desired within a restricted space, especially in portable apparatus. The plan would be to construct a short-period pendulum which would respond as an accelerometer, and have it actuate a torsion-pendulum of any period in (theoretically) the same manner that accelerations are applied to the torsion-head of the torsion-pendulum analyzer. The torsion-pendulum would then be actuated by the earthquake-motion itself through the medium of the accelerometer-pendulum. It is believed that any mechanical difficulties involved could be surmounted. Such a set-up would be especially valuable in serving as a long-period vertical-motion seismometer which would have the same constants as a set of similarly designed horizontal pendulums.

For all set-ups with long-period pendulums the device functions effectively as a double-integrator as evident from the fact that displacement is obtained direct from acceleration in all cases where the torsion-pendulum period is about three times the period of the waves analyzed. As there is almost no limit to the periods obtainable with a torsion-pendulum, it follows that it can be made to function as a double integrator over a great range of wave-periods, or miscellaneous curves if applied in other fields.

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COMMENT ON F. W. SOHON'S PAPER "TRANSFORMING THE STEREOGRAPHIC MAP"

W. L. G. Joerg

The method described in this paper of transforming the zenith of a stereographic map is of importance in its bearing on the construction of such maps for the determination of the location of earthquake-epicenters from seismograph-records. (Although no mention is made in the paper, it is here assumed that its presentation at the joint meeting of two seismological groups envisaged this application of the method.) The stereographic projection is one of two among the group of azimuthal projections (the equidistant, or Postel's, being the other) that are the most appropriate for this purpose, as has been pointed out by a number of writers. As the geographic position of a given seismographic station is made to be the point of tangency of the plane of projection with the sphere, a different grid has to be constructed or computed for each station. In the case of the stereographic projection the grid may be constructed rather simply since the meridians and parallels are arcs of circles. Whether the method proposed in the present paper of deriving one grid from another by changing the zenith offers advantages in time-saving over the conventional method of independent construction is a question it would be of interest to settle by drawing two grids for the same station by the two different methods.

The publications referred to above that deal with the appropriateness of the stereographic and Postel's projections are as follows: R. de Kővesligethy, Comptes-Rendus Réunion Assoc. Internat. de Séismologie, The Hague, September 21-25, 1907, p. 147; Imre Jánosi, Bull. Soc. Hongroise de Géogr., Edit. Internat., v. 37, pp. 35-39, 1909; W. L. G. Joerg, Annals Assoc. Amer. Geographers, v. 2, pp. 49-54, 1912; E. Rudolph and S. Szirtes, Petermanns Mitt., v. 60, I, 1914; J. Howells (not published), Construction of an azimuthal projection for seismographic-station use, paper read at the ninth annual meeting of the Eastern Section of the Seismological Society of America held at Fordham University, New York, April 30-May 1, 1934. On one or the other of these projections published maps exist for the following stations: Budapest (Jánosi, op. cit.); Apia, Samoa (Joerg, op. cit.); and Strasbourg (Rudolph and Szirtes, op. cit.).

American Geographical Society,
New York, New York

[Note by Father Sohon--The transformation was proposed merely as a mathematical curiosity. In reply to a question proposed by Dr. Hodgson, I expressly stated that I thought it would be faster to recompute rather than to employ the method in a practical problem. I might add, however, that the graphical solution of the problem of finding the true length of the arc of a great circle is a practical application of the method, in which the great circle in question is transformed into the primitive circle. But I propose to eliminate even this construction. The whole purpose was therefore theoretical and had only the intention of giving a better insight into the projection.]

AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

SECTION OF METEOROLOGY

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SYMMETRY-POINTS IN THE AIR-PRESSURE

B. Haurwitz

Since 1923 atmospheric periodicities of longer and shorter duration have been studied at the Geophysical Institute, Leipzig, by Weickmann and his collaborators. These studies started out with the discovery of symmetry-points in the pressure-curve by Weickmann [see 1 of "References" at end of paper]. Two examples of such symmetry-points are given in Figures 1 and 2. The full line in both is constructed from the morning readings of the barometer reduced to sea-level for the dates as indicated at the top of each Figure. The dotted line is the same pressure-curve but reversed at the date of the symmetry-point. It will be seen that the symmetry-point for Hamburg in Figure 1 occurs January 21, 1921, and that for Edmonton July 3, 1922. The dates corresponding to the reversed curve are given on the lower margin of each Figure. Each value of pressure n days to the left of the point of symmetry on the full curve is thus equal to a value n days towards the right after the symmetry-point on the dotted curve. It will be seen that both the original and the reversed curves agree fairly well in their general features.

To find such symmetry-points the original pressure-curve is copied on transparent paper, this copied curve is reversed and moved parallel to the original one, until the position of best agreement between the curve and its reverse is obtained. Figure 3 explains the origin of symmetry-points in a schematic fashion. If periods exist in the variations of the air-pressure, it is possible to approximate the actual pressure-curve by a number of sine-curves. The number of sine-functions necessary depends, of course, on the character of the curve under consideration. A sine-curve is symmetrical about its extreme values. If we have a curve composed of a number of

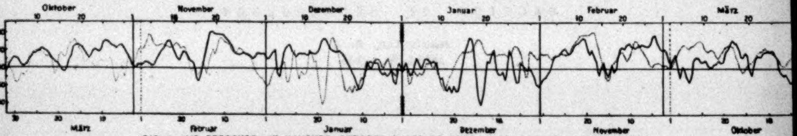

FIG. 1—AIR-PRESSURE AT HAMBURG, OCTOBER 3, 1920 TO APRIL 1, 1921 (AFTER L. WEICKMANN)
▮=SYMMETRY-POINT JANUARY 1 1921

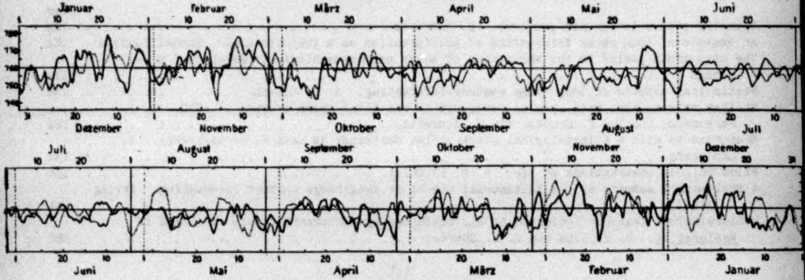

FIG. 2—AIR-PRESSURE AT EDMONTON, JANUARY 1 TO DECEMBER 31, 1922 (AFTER L. WEICKMANN)
▮=SYMMETRY-POINT JULY 3, 1922

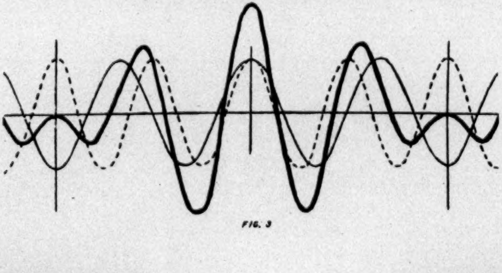

FIG. 3

sine-curves and if the extreme values of the constituents coincide, the complex curve will be symmetrical about this point. In Figure 3 the heavy curve is composed of two constituents indicated by a dotted and a full curve. In the center of Figure 3 both curves have a maximum, consequently the sum of both components indicated by the heavy curve has a symmetry-point there. It is not necessary that only maxima or only minima coincide. A symmetry-point occurs always when extreme values in general coincide. Thus we find two other symmetry-points to the left and to the right where the one component has a maximum and the other one a minimum. There is another type of symmetry-points which, however, has been found of no meteorological interest.

The particular value of symmetry-points for the study of periodicities consists in the following. Every curve can be represented by a sum of trigonometric functions with sufficient accuracy, provided it fulfills certain very liberal mathematical conditions. In general, however, this harmonic analysis will have no meteorological interest since the amplitudes of the different terms will all be of the same order of magnitude and therefore no period will be dominant. In such a case it is most unlikely that a symmetry-point will be found since it is highly improbable that the extreme values of all the components of the original curve coincide. On the other hand, if we have found a symmetry-point, we may conclude that some very few constituents have much higher amplitudes than the rest and give the main trend of the pressure in the interval under consideration, because a coincidence of the extremes as indicated by the symmetry-point is evidently by far more probable if only a few terms in the harmonic series are important. Examples of the harmonic analysis during times with symmetry-points will be found in [1] and [2]. Thus the symmetry-points furnish the student of atmospheric periodicities with a tool to decide for which time the harmonic analysis will give significant results. In some cases it is of course possible to see directly from the original curve that it contains a period. But in many less obvious cases the method of symmetry-points will prevent unnecessary efforts.

The investigations at Leipzig have shown that in Europe and apparently in North America too many winters are dominated by a period of duration 20 to 24 days. Mildner [3] and Weickmann [4] have studied this wave and its distribution over the whole Northern Hemisphere in great detail for the winter 1923-24. The map of the geographical distribution of the amplitudes (reproduced in [2]) shows the velocity and direction of propagation of this wave. From both maps it will be seen that this wave represents a pulsation of the arctic air-masses with fairly regular outbursts of cold air which affect Europe, Asia, and North America. Schwerdtfeger [5] has given a theory of this wave. After an outburst of polar air this air is gradually heated in the lower latitudes and the contrast of temperature between temperate and polar regions is reestablished until after about 24 days it has become large enough for a new outburst. His theory is confirmed by the behavior of the surface-temperature. The temperature shows according to Weickmann [6] the same period and similar distribution of amplitude and phase as the pressure-wave. We should thus expect that the appearance of the wave at mountain-stations and in the free atmosphere would also indicate that the phenomena connected with the wave occur in the lower troposphere. This is actually the case [7, 15].

The 24-day wave has been discussed in detail here in order to show by an example the methods which have been used in the study of these phenomena by Weickmann and his collaborators. Some other related investigations may be mentioned briefly. There seems to occur during some winters a wave with a period of 36 days which represents according to Lettau [8] a free oscillation of our atmosphere.

The correlation of pressure-waves at different stations has been studied by Griessbach [9].

A wave with a period of three years in pressure and temperature has been investigated by von Schubert [10] and by Rietschel [11]. An oscillation of the temperature-difference between summer and winter with a period of 16 years, which was discovered by A. Wagner [12], was represented in its distribution over the whole Earth by Weickmann [13]. He found that maximal amplitudes exist over land as might be expected. It is highly probable that this oscillation represents a pulsation of the intensity of the general circulation. Seidel [14] has shown that a period of duration 16 years also appears in the precipitation.

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AN EXAMPLE OF LONG-RANGE FORECASTING OF PRECIPITATION ON A DRAINAGE-AREA

Samuel Shulits

Long-range prediction of precipitation and its value in hydraulic engineering is exemplified by its application to the drainage-area of Teigitsch Creek in Styria, Austria. Its drainage-area at the Langmann Dam is 170 sq km (42,000 acres) and the yearly mean flow is 316 cu m/sec (127 cusecs).

The basis of the forecast is the fact that some time elapses before the weather in Continental Europe changes as a result of fluctuations of the meteorological elements in the three atmospheric centers of action controlling European climate, namely, Iceland, the Azores, and Russian Siberia. By the method of partial correlation W. von Kesslitz [see 1 of "References" at end of paper] ascertained the relation between the monthly precipitation on the drainage-area of the Teigitsch and the monthly means of temperature and barometric pressure for preceding months in the three atmospheric centers of action governing Europe. He used the meteorological observations at Stykkisholm and Seydisfjord in Iceland or Thorshaven in the Färöer Islands (the Iceland low), and also those at La Coruna (the Azores high) and Leningrad (Russian-Siberian center of action). The computations required several years. The resulting equations for the monthly precipitation, P, in mm are compiled in Table 1 [2, p. 33]. In these equations B is the excess of the actual monthly mean barometric pressure above 700 mm, that is, for a barometric pressure of 740 mm the value of B = 40, and T is the monthly mean temperature in °C.

Table 1--Correlation-equations for precipitation on Teigitsch drainage-area

Month	Equation	Place of observation and time for B and T	Mean error per cent
January	$P = + 50.3 - 0.351B - 12.58T$	Stykkisholm, December	31.6
February	$P = + 535.1 - 5.49B - 14.29T$	La Coruna, December	37.7
March	$P = - 160.1 + 4.96B + 10.85T$	Stykkisholm, December	35.1
March	$P = + 113.4 - 2.36B + 8.57T$	La Coruna, December	36.2
April	$P = - 211.0 + 4.55B$	La Coruna, January	32.2
May	$P = + 268.0 - 17.50T$	La Coruna, January	22.4
May	$P = + 47.2 + 3.25B - 4.70T$	Stykkisholm, January	25.1
June	$P = + 351.6 - 1.13B - 16.4T$	La Coruna, March	15.1
July	$P = + 473.6 - 5.38B - 17.1T$	Thorshaven, March	22.0
July	$P = - 232.8 + 3.11B + 17.3T$	La Coruna, March	23.3
August	$P = + 122.0 + 12.04T$	Stykkisholm, April	26.7
August	$P = - 156.5 + 4.86B$	St. Petersburg, December	25.1
September	$P = + 334.0 - 6.06B + 11.38T$	Stykkisholm, July	31.1
October	$P = - 150.5 + 4.71B - 15.52T$	Stykkisholm, July and August	27.0
November	$P = + 732 - 10.9B$	La Coruna, September	37.8
November	$P = - 263.5 + 0.898B + 29.3T$	Thorshaven, September	44.7
December	$P = - 1504.5 + 25.0B$	La Coruna, July	30.3
December	$P = + 377.7 - 5.74B$	Thorshaven, October	33.8

Despite the relatively small drainage-area, the agreement between observed precipitation and that predicted with the aid of the equations is good enough to demonstrate the practicability of this method.

Further use of the correlation-method enabled von Kesslitz to set up equations for the monthly runoff of the Teigitsch Creek at the Langmann Dam to permit a more efficient operation of the Langmann Reservoir for power-purposes. The runoff, R, in mm is expressed in terms of the monthly precipitation, P, in mm of the months governing the runoff of the desired month. The equations are given in Table 2 [1;2, p. 61]. In most of the equations the precipitation of the month for which the runoff is desired must be known; this can be determined with the aid of the equations in Table 1. In Table 2, P (VII to XII) means the total precipitation of July to December inclusive; T (II + III) means the sum of the mean monthly temperatures of February and March, etc. The inclusion of this temperature-term increases the accuracy somewhat.

Table 2--Equations for monthly runoff of Teigitsch Creek at Langmann Dam

Month	Equation	Mean error
		per cent
January	$R = -\ 8.6 + 0.0704P(\mathrm{VII\ to\ XII})$	± 10.0
February	$R = +\ 6.7 + 0.0422P(\mathrm{VIII\ to\ I})$	± 7.7
March	$R = +\ 13.2 + 0.0721P(\mathrm{X\ to\ III})$	± 14.1
April (1)	$R = -\ 2.7 + 0.118\ P(\mathrm{IX\ to\ IV}) - 1.42T(\mathrm{II} + \mathrm{III})$	± 13.5
April (2)	$R = -\ 12.0 + 0.122\ P(\mathrm{IX\ to\ IV})$	± 15.4
May (1)	$R = +\ 56.0 + 0.373\ P(\mathrm{IV} + \mathrm{V}) - 4.38T(\mathrm{III} + \mathrm{IV})$	± 14.3
May (2)	$R = -\ 51.9 + 0.632\ P(\mathrm{IV} + \mathrm{V})$	± 16.3
June	$R = +\ 18.0 + 0.200\ P(\mathrm{V} + \mathrm{VI})$	± 12.0
July	$R = -\ 8.9 + 0.239\ P(\mathrm{VI} + \mathrm{VII})$	± 15.7
August	$R = -\ 23.9 + 0.346\ P(\mathrm{VII} + \mathrm{VIII})$	± 19.1
September	$R = +\ 3.9 + 0.250\ P(\mathrm{VIII} + \mathrm{IX})$	± 15.8
October	$R = -\ 20.3 + 0.233\ P(\mathrm{VIII} + \mathrm{IX} + \mathrm{X})$	± 8.8
November	$R = -\ 14.2 + 0.165\ P(\mathrm{VIII\ to\ XI})$	± 7.1
December	$R = +\ 8.2 + 0.167\ P(\mathrm{X} + \mathrm{XI} + \mathrm{XII})$	± 17.3

This method yields more accurate results than the use of runoff-coefficients. The results agree well with observed runoffs. Local storms, however, may cause appreciable discrepancies on small areas.

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THE NINE-MONTH PERIOD IN THE VARIATIONS OF SOLAR AND METEOROLOGICAL PHENOMENA

H. W. Clough

The internal constitution of the Sun, notwithstanding its gaseous nature, is unsymmetrical with respect to the plane of its equator. The Northern and Southern hemispheres differ widely in their manifestations of spot-activity. For months, one hemisphere may be active while the other hemisphere is quiescent. In fact, there seems to be a decided tendency to alternation of activity over short periods of time. During the years 1914-34, except the two years of minima, 1923 and 1933, the mean monthly areas of thw two hemispheres showed a rather pronounced negative correlation, -0.32.

When monthly ratios of the northern spotted area to the total area are smoothed and plotted, recurrences of varying lengths are disclosed. Employing 12-month means, a 2 1/2-year period is evident, as I have previously pointed out [see 1 and 2 of "References" at end of paper]. When the ratios are smoothed by a four-term formula, $(a + 2b + 2c + d)/6$, a shorter period of about nine months is disclosed. This period has persisted at least since 1873, as shown by a study of the Greenwich solar observations. The average length of the period for the past 60 years has been 9.25 months, while the most frequent length is calculated to be 9.1 months. The length of the period varies between seven and twelve months. This range is comparable to that of the 11-year period of total spottedness. The variations in length are not fortuitous but are definitely related to the occurrence of phases of the 2 1/2-year period.

There are certain regions on the Earth where the meteorological response to solar variations is well defined. Alaska is one of these regions. When monthly departures of pressure at Tanana are smoothed, a nine-month period can be readily traced with maxima occurring about six months after the solar maxima of northern excess of spottedness. From 1913 to 1923 the average lag was five months; since 1923 it has averaged seven months.

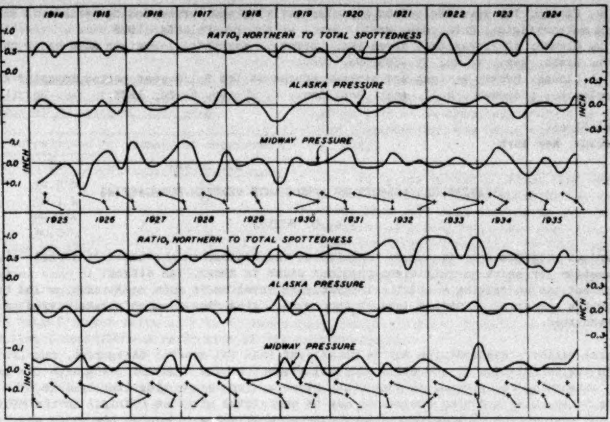

FIG. 1—SOLAR AND ASSOCIATED METEOROLOGICAL PHENOMENA

Concurrently with the maxima of pressure over Alaska occur minima of temperature over the regions to the southeastward, extending into the United States.

The barometric seesaw between stations in high and low latitudes is well exemplified by the opposition in pressure between Alaska and Midway Island. The latter station shows the nine-month pressure-oscillation very clearly, with epochs nearly coincident, on the average, with those at Tanana. At times they precede, at other times they follow.

Another station showing the nine-month variation satisfactorily is Madeira, in the Eastern Atlantic. Its epochs occur on the average 0.4 month after similar epochs at Midway Island. Their epochs may therefore be regarded as nearly coincident, and by averaging the two series of epochs at these low-latitude stations, normal epochs are obtained for comparison with pressure- and temperature-epochs in high latitudes and with the solar epochs.

The recent severe winter has been characterized by abnormally high pressure in high latitudes and correspondingly low pressure in low latitudes. This pressure-distribution with the associated low temperature may be regarded as largely related to the following meteorological conditions.

In the first place, a minimum phase of the seven-year variation [3] in temperature in the United States is due around 1935 or 1936. Furthermore, the epoch of maximum pressure in Alaska in the 2 1/2-year variation occurred approximately in the winter of 1935-36 [4]. The mean pressure for the year 1935 in Alaska was the highest of record.

Finally, the nine-month period in the variation of pressure at Midway Island shows a pronounced minimum epoch centered approximately January 25. Pressure in the Eastern Atlantic Ocean, south of latitude 50°, likewise remained exceptionally low during the entire winter. Abnormally high pressure prevailed in high latitudes.

Thus the concurrence of the minimum phases of three important weather-periods, each contributing to a lowering of temperature below normal, occurred near the minimum phase of the annual period, so that wintry conditions were greatly intensified as a consequence of this unusual coincidence.

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STATISTICAL ASPECTS OF LONG-RANGE WEATHER-FORECASTING

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Various attempts have been made to forecast the weather on the basis of certain statistical relationships for which no sufficient physical cause is known. An attempt is made in this paper to point out the underlying statistical principles involved in such relationships and to indicate how the operation of simple laws of chance will give rise to such relationships as have been discovered.

These weather-relationships may be classified into two general categories, namely: (1) Those based on the correlation of one meteorological element at one time and place with the same or another meteorological element at some other place or some other time (for example, the pressure over the Sahara Desert during one season may be correlated with the rainfall in the Mississippi Valley the next season, or the temperature over a certain region during one month may be correlated with the temperature over the same region many months later); (2) those based on the cyclic character of certain meteorological elements from which it is assumed that maxima or minima observed in the past will be repeated at a certain definite time in the future.

The general procedure employed to discover relationships of the first category is simple. The investigator collects various series of data and looks for some such relationship in them. If none is found the data are rejected and new series employed until suitable relationships are discovered. There seem to be no restrictions upon the kind of data used, nor upon the times or regions from which they are selected, the objective being to find two series of data which exhibit a relationship of the type desired. Sometimes the study is terminated by merely plotting the data or pointing out isolated cases in which the supposed relationship is most manifest. In other cases the investigator employs the more elegant methods of mathematical statistics which frequently lead him only to more insidious conclusions.

The practice in such treatment is to calculate the correlation-coefficient, r, and discuss it. If r is small no relationship is said to exist, but if r is appreciable one is said to exist and values of r as great as 0.3 are so considered, although they would have little value for prognostication even if real. The error of r is calculated by the formula $(1 - r^2)/\sqrt{N}$ in which N is the number of pairs of data from which the coefficient has been computed. The probability is very low that a value of r several times as great as its error should arise through the operation of chance. The alternative conclusion is immediately accepted that the relationship rests upon some unknown operation of the laws of Nature.

The fallacies involved in this method are patent. The value of N to be used in computing the error is a matter of considerable importance. The formula for the error of r is developed on the assumption that each pair of values is completely independent of every other pair and this assumption has no a priori justification when meteorological phenomena are treated. In fact, quite the reverse condition exists; for example, the temperature in June is likely to be much more closely associated with the temperature the following July than it is with the July a year later. Furthermore, the process of smoothing, which is so frequently employed before calculating the correlation-coefficient, definitely eliminates the quality of independence which might otherwise exist.

Even though the error of r may have been correctly calculated, many of these relationships exhibit a value which it is difficult to believe arose strictly through the operation of the laws of chance. A simple illustration will demonstrate their origin best. Suppose that there are two boxes containing a large quantity of numbered cards, the numbers in each box being, as the statisticians say, "normally distributed." Two cards are drawn simultaneously, one from each box, and their numbers are recorded on a sheet of paper. Suppose that this process is repeated 50 times until 50 pairs of numbers have been obtained. One would expect the correlation-coefficient calculated from these 50 pairs of numbers to be quite close to zero. But if 100 such correlation-coefficients were calculated from 100 such series of independent numbers it might be reasonably expected that one or more of them would be appreciable in magnitude. Table 1 shows the expected number of correlation-coefficients for certain limits of magnitude for just such a case as this calculated in accord with the principles of mathematical statistics (Tables for statisticians and biometricians, Part II, p. 208).

Table 1--Frequency of occurrence of various correlation-coefficients due to chance in 100 sets of 50 pairs of data each

Observed correlation		Number of occurrences
From	To	Out of 100
0.0	±0.075	40
±0.075	±0.175	38
±0.175	±0.275	17
±0.275	±0.375	4
Greater than +0.375		1

It is the writer's belief that every relationship of this nature which he has examined arose from just such origins as have been described and consequently are absolutely worthless for prognostication. In fact, one investigator naively states that of many possible relationships (over 300) studied only one yields an appreciable value of r. He then proceeds to reject all the cases for which r was small and to proclaim that the large value of r is significant for prognostication. One would expect to find a "significant" value of r if he looks long enough; in fact, failure to find such a one would in itself constitute a refutation of the laws of chance.

More intriguing but more seductive to the reason are prognostications based upon the discovery of cycles in meteorological phenomena. Although various elegant and powerful tests (J. Bartels, Terr. Mag., v. 37, pp. 1-52, 1932, and v. 40, pp. 1-60, 1935) have been devised to measure the statistical reality of alleged periodicities, few of the cycle-analysists have availed themselves of them. Even with these tests an investigator is likely to arrive at erroneous conclusions owing to certain characteristics of meteorological, social, economic, and other phenomena. Time-series of meteorological data constitute what may be termed correlative series, that is, each datum is to some extent dependent upon those immediately preceding it. For example, if at some instant the weather is fair the prognostication that it will still be fair an hour later stands a high chance of being correct. A forecast that the weather will still be fair six hours later stands less chance of being correct, while if the time-interval is sufficiently increased the forecast becomes a pure guess. To state this in mathematical language, if the various data of the series be designated by a_1, a_2, a_3, ... etc., the nth term of the series is given by the following relation

$$a_n = ra_{n-1} + \epsilon$$

in which r is less than unity (being in a sense a correlation-coefficient) and ϵ is some variable quantity, positive or negative, which is independent of every other term in the series. Such a series is quite similar to an accumulative series which some statisticians have pointed out exhibits cyclic features. It has this distinct character, however, that the value of no term can be very greatly different from the mean which is zero. The values of a in the series are assumed to represent departures from some average value for the series, for example, the excesses or deficiencies of rainfall, and thus may be either positive or negative.

The physical cause of a correlative series in meteorology is clear. Considering the rain-

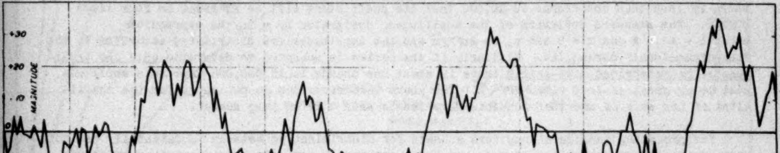

FIG. 1—CYCLIC CHARACTER OF CORRELATIVE SERIES OF FORM $a_n = ra_{n-1} + \epsilon$ (r=0.9; ϵ=RANDOM NUMBERS -9 TO +9)

fall over the central portion of a continent, a year during which the rainfall has been very great will result in the accumulation of considerable ground-water which by its subsequent evaporation through the soil will supply humidity to the air giving rise to further rainfall and tending to perpetuate the "wet cycle" until the development of some other condition causes a change in this trend. Regardless of the cause, it is an observed fact which admits of no doubt that such conditions do exist. They are not to be confused, however, with the setting in of a rainy season in the tropics and similar phenomena which are closely associated with periodic astronomical phenomena and recur as regularly as night follows day.

A typical correlative series of this form is represented in Figure 1. Many of the curves showing weather-cycles bear a close resemblance to the one depicted. It is possible to consider this curve as indicating a cycle of continually increasing length or a cycle of constant length which underwent a phase-change near the middle of the series--either point of view is allowable in cycle-analysis. However, the fact is that this series was formed from a series of random numbers determined in very much the same manner as the winning number in a "numbers game." The initial term of the series was taken as zero. It is pertinent to remark that the series represented was the first and only one of its kind which the writer attempted to demonstrate this point and is not the single one of many others which failed to exhibit cyclic tendencies. No smoothing process was applied to the data. An investigation of the mathematical properties of a correlative series and of the methods employed for the discovery of cycles will indicate how so many have been found which have no physical basis and fail to exhibit that fundamental property of periodic phenomena--regular recurrence.

The procedure of cycle-analysis is to arrange a series of data in their proper order, select a time-interval over which the data exhibit a tendency for recurrence, compute the average variation over this period, and then assume the remainder of the series which has not been observed will reproduce the wave-form of the past. It is important to note that in general no predetermined length of the cycle is used, but rather that length which best fits the data--a point of considerable importance from the statistical viewpoint. Frequently the data are smoothed by a process of overlapping means, a procedure which adds nothing to their value but actually obscures a very important characteristic--their variability. It is the writer's opinion that no such process of smoothing should ever be used except for graphical illustration.

There are several types of variations which exhibit periodic characteristics: (1) The persistent periodic variations, such as the daily variation in temperature, which are repeated with a high degree of regularity over long stretches although individual intervals may exhibit considerable irregularity, and which become more accurately defined as the number of observed occurrences is increased without limit; (2) quasi-persistent periodic variations, such as arise when a number of cyclonic and anti-cyclonic areas pass over a station in somewhat regular succession, which are more clearly defined in a short series of observations but which cannot be considered periodic over long intervals; and (3) the cyclic variations, arising from correlative phenomena.

If $a_1, a_2, a_3, \ldots\ldots a_n$ is a series of equally spaced random numbers which are normally distributed, representing, for instance, daily or monthly values of some variable, it may be shown that the standard deviation of the coefficients of the sine- or cosine-waves--obtained by analyzing the series into its Fourier components--is $\sigma\sqrt{2/n}$ where σ is the standard deviation (root-mean-square deviation) of the values a. The amplitudes of these coefficients will be normally distributed like the original series. From these considerations it may be concluded that if the series is analyzed to determine only one component of predetermined wave-length there is less than one chance in 10,000 that its coefficient will be as great as four times $\sigma\sqrt{2/n}$. The standard deviation of the amplitudes, designated by c in the expression $c \cos(t + \varphi) = A \cos t + B \sin t$, is $2\sigma/\sqrt{n}$ and the amplitudes are distributed according to the "two-dimensional" normal law. Similarly if the series is analyzed to determine only one amplitude of predetermined wave-length there is about one chance in 10,000,000 that this amplitude will be as great as four times $2\sigma/\sqrt{n}$. The above considerations do not apply for the coefficient of the wave of shortest possible wave-length when n is an even number.

The preceding considerations form a basis for discriminating between fundamentally periodic characteristics of any series of data and those apparently periodic characteristics which may arise from the operation of the laws of chance in a purely random series of data. The investigation of periodicities is complicated by what Bartels (Terr. Mag., v. 37, pp. 1-52, 1932, and v. 40, pp. 1-60, 1935) has described as quasi-persistent periodicities--those which have a basic tendency toward recurrence but which persist only for a limited length of time. The best example of these periodicities in geophysical phenomena is offered by phenomena associated with sunspots. In order to produce certain terrestrial effects the sunspots must be on that side of the Sun which is directed toward the Earth, but as the spots rotate with the solar atmosphere their effects are periodic, having a period of about 27 days which is the average rotational period of the solar atmosphere. After a number of rotations a group of spots will disappear causing the termination of that series of 27-day recurrences. The development of new spots gives rise to another series. Criteria for the study of such phenomena are presented in the papers previously cited.

On the other hand, a correlative series has no such underlying periodic nature but owing to certain properties it may appear to have them. Investigation of the mathematical properties of such a series indicates the origin of these characteristics. Defining a correlative series as before--one in which the nth term is given by $a_n = a_{n-1} + \epsilon$, ϵ being a random quantity--it is possible to formulate these properties. For simplicity it will be assumed that the values ϵ are distributed according to the normal law. It will be further assumed that the series is very long so that statistical laws will be thoroughly applicable.

If σ_ϵ is the standard deviation of the values ϵ then the standard deviation of the values a is given by $\sigma_a = \sigma_\epsilon \sqrt{1 + r^2 + r^4 + r^6 \ldots\ldots}$ and the values a for the entire series will be distributed according to the normal law. The important difference exists, however, that although the values of a for the entire series are distributed according to the normal law these values for a limited portion of the series are not so distributed. For illustration, in the case where $r = 0$, which is a random series, the value of a_n is equally likely to be positive or negative, regardless of the value of a_{n-1}, whereas for a correlative series a large value of a_n is quite likely to follow a large value of a_{n-1}. This property is graphically represented in Figure 2 in which the probability that the nth value in the series shall be equal to or less than zero for $a_0 = \sigma_a$ is plotted against n for various values of r. For $r = 0$ any value of the series is equally likely to be positive or negative but for large values of r the occurrence of a large value of a series prejudices the immediately succeeding terms of the series.

By making certain simplifying assumptions it is possible to calculate the standard deviation of the coefficients of the cosine- or the sine-terms obtained by submitting such a series to Fourier analysis. The standard deviation depends both on the frequency of the harmonic and the value of r for the series. A plot of the standard deviation for a wave whose length is 12 times the time-interval between successive values of a is shown in Figure 3 expressed as the ratio of the standard deviation of the terms in a correlative series to the standard deviation of the terms in a purely random series. For $r = 0$ the ratio is unity. The ratios also apply for the

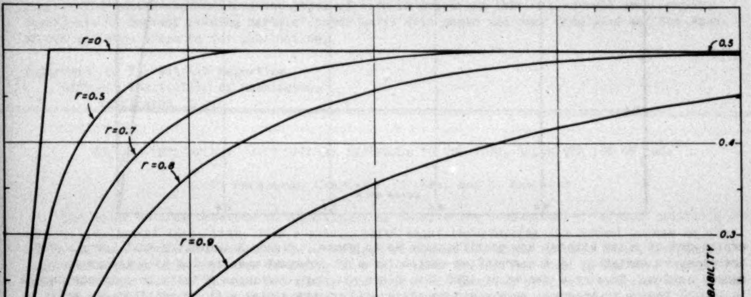

FIG. 2—PROBABILITY THAT n^{TH} VALUE (a_n) IN CORRELATIVE SERIES $a_n = ra_{n-1} \pm \epsilon$ SHALL BE ≤ 0 WHEN $a_0 = +\sigma_a$

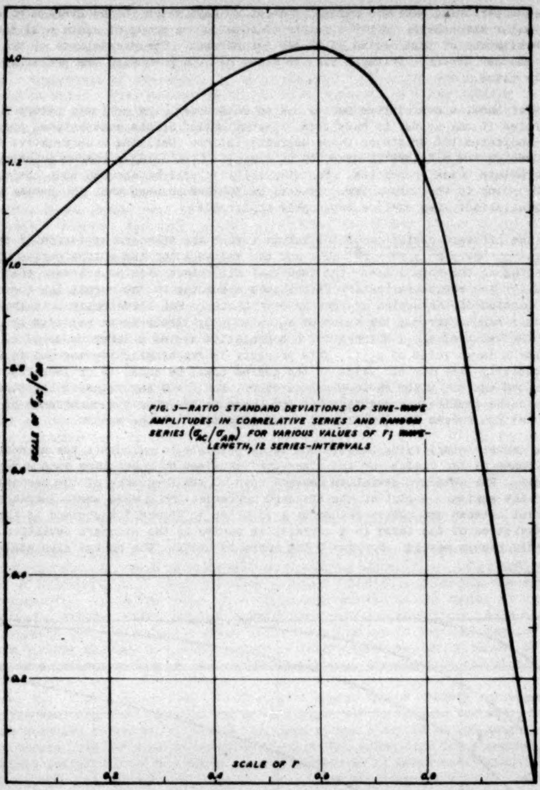

FIG. 3—RATIO STANDARD DEVIATIONS OF SINE-WAVE AMPLITUDES IN CORRELATIVE SERIES AND RANDOM SERIES (σ_{AC}/σ_{AR}) FOR VARIOUS VALUES OF r; WAVE-LENGTH, 12 SERIES-INTERVALS

amplitudes of waves without any qualification as to phase. Figure 3 indicates that for r = 0.6 the standard deviation in a correlative series for a 12-interval wave is 1.4 as great as in a random series. Thus if a series of 1200 data has a standard deviation σ there is only one chance in 10,000 that a 12-interval wave would be discovered in the series with an amplitude as great as 0.081σ if the data constitute a random series. The discovery of such a wave would lead to the belief that the wave represented some physical reality. If, however, the data formed a correlative series with r = 0.6 there would be one chance in 100 of finding such a wave, even though there might be no physical cause for its existence other than the fact that the series is correlative. Ignoring the properties of a correlative series has caused the acceptance of various fictitious periodicities by many investigators.

A very interesting point is brought out by Figure 3. Although for values of r less than about 0.85 the ratio of standard deviations of the amplitudes of the waves from a correlative series to those from a random series is greater than unity, for greater values of r the ratio becomes less than unity, approaching zero as r approaches unity. The physical significance of this at first astonishing condition may be realized by considering the test for the reality of the diurnal variation of temperature. Clearly the standard deviation of the values of a to be used to test the reality of the diurnal variation should not be the standard deviation derived from considering all the hourly values during a year, but the standard deviation derived from a smooth curve from which seasonal and similar variations have been removed.

Another consideration also should be respected in investigations of "hidden" periodicities. The tests for reality which have been described apply when the length of the period investigated is predetermined from some source other than the data. In cycle-analysis this is not the customary procedure, the length of the period being selected after inspecting the data. Thus if p_1 denotes the *a priori* probability of finding a significant amplitude for the period-length t_1, p_2 for period-length t_2, etc., then the probability of *not* finding a significant amplitude for t_1 is $1 - p_1$; for t_2 is $1 - p_2$; etc. Assuming for simplicity that all values of p are equal, the chance of not finding a significant amplitude for t_1, t_2, etc., is $(1 - p)^n$ in which n is the number of periods investigated, even though the investigation might have been performed only by inspection. Since the probability of finding a significant amplitude for *some* period is the complement of not finding *any*, the probability of finding a significant period may be written $1 - (1 - p)^n$ which may closely approach unity even though the value of p may be small. Some restrictions must be placed upon this consideration owing to the finite character of the data which may be used. This point has been brought out before by Ad. Schmidt and Sir Gilbert Walker.

Acknowledgment--The writer wishes to express his indebtedness to Dr. J. Bartels from whose writings the discussion of persistent and quasi-persistent periodicities has been freely drawn. The general considerations of a correlative series have been mentioned in his writings (referred to as the principle of conservation) and the conclusions reached in this paper have been anticipated. As far as the writer is aware the explicit formulation of the correlative series and the quantitative treatment presented in this paper are new. An approach to the problem is given by Bartels in his formulation of the concept of quasi-persistence, but such true periodicities which persist only for a limited time are distinct from the cyclic character of a correlative series although the distinction is sometimes very difficult to establish.

Note added May 20, 1936--While the material pertaining to the correlative series in this paper was being developed a paper by J. Bartels (Zur Morphologie geophysikalischer Zeitfunktionen, Berlin, SitzBer. Ak. Wiss., No. 30, 1935) was received by the writer in which similar conclusions were reached. A formula for the expectancy of amplitudes in such a series developed by K. Stumpff (paper to be published in den Veröffentlichungen des Met. Univ. Inst. Berlin) is given in that paper. The writer regrets that the press of work in preparing this and several other papers caused him to neglect reading Bartels' paper until this paper had been completed and the manuscript had been prepared for publication.

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ECLIPSE-METEOROLOGY, WITH SPECIAL REFERENCE TO THE TOTAL SOLAR ECLIPSE OF 1932

S. P. Fergusson, Charles F. Brooks, and B. Haurwitz

The solar eclipse presents an opportunity to observe the consequence of a rapid shutting off and restoration of insolation, like a quick, brief night interrupting the normal course of the day's weather. The North American total eclipse of August 31, 1932, crossed a well-populated region of considerable physical diversity at a time when the Sun was high in the sky. Support from the Milton Fund of Harvard University and from J. J. Storrow, Jr., made it possible for the Blue Hill Observatory to undertake an ambitious program of meteorological observations, both surface and aerological, and to collect data from nearly 300 cooperating stations of the United States and Canadian weather-services, astronomical parties, forest-services, power-companies, the Appalachian Mountain Club, and numerous individuals. The complete monograph with rather full details, presented in abstract here, is to be published as No. 3 of Harvard Meteorological Studies.

Meteorological instruments (S. P. Fergusson)--While ordinary apparatus can measure changes of radiation and temperature caused by an eclipse, instruments of more than ordinary sensitivity are necessary to detect the consequent variations of pressure and wind and to establish the nature of changes in absolute humidity. So small are any changes of pressure that it seems futile to hope to detect them except by means of a barograph having a scale of at least 5 to 1; if an aneroid is used compensation for temperature-change, if any, becomes important; if a mercurial, the bore must be sufficiently large (20 to 25 mm) to minimize the effects of capillarity. The variations in direction of the wind, usually amounting to only a few degrees of azimuth, are best recorded by an anemoscope of the Draper pattern whose record can be read to 1°. Since appreciable time is necessary to read velocities, the scale of the anemometer should permit readings to 0.1 m/s. Non-recording "hand" anemometers and vanes are satisfactory and economical, but, in view of attention needed by other instruments during the eclipse, light, open-scale recorders are preferable. A Draper anemoscope combined with a cup-anemometer into a single instrument recording direction and velocity has proved to be very satisfactory. Also, because of the rapidity with which changes occur, thermographs and hygrographs should be more freely exposed than is customary; an open shelter of the French or Russian type is recommended.

For the study of the eclipse of 1932, the special stations of the Blue Hill Observatory were equipped with instruments designed by S. P. Fergusson according to experience derived from studies of earlier eclipses. All had time-scales of 40 mm an hour, permitting readings every two minutes, and with as open scales for the various elements as seemed practicable. Six thermohygrographs and parts for seven anemographs were constructed by the Mann Instrument Company; the anemographs were completed by F. B. and P. A. Towle. Three aneroids and two Draper weighing mercurial barographs with scales of 5 or 5.5 to 1 were constructed and one Richard aneroid rebuilt with a 3 to 1 scale. The mercurial barographs had tubes of 23-mm internal diameter. Estimates to 0.01 mb were possible from the records of both types. Six black-glass nephoscopes were built to order by the Mann Instrument Company, and some 30 sling-psychrometers, by Henry J. Green, were borrowed from the Harvard students' meteorological laboratory. These psychrometers had long cords, which permitted them to swing on a radius of about one meter, thereby insuring ample ventilation.

The special meteorological stations (S. P. Fergusson)--To avoid local adverse weather, to measure local differences, and to make possible synoptic mapping or at least comparisons on opposite sides of the path of totality, a network of 23 stations was equipped or maintained by Blue Hill Observatory and experienced cooperating observers. Five of these--Mt. Washington, Mt. Moosilauke, Mt. Chocorua, Sugar Hill, and Blue Hill--were on isolated peaks. Four--Pinkham Notch, Conway, Berlin Mills, and Lancaster--were in valleys among the highest mountains in New England. Eight--Concord, Limerick, Douglas Hill, St. Johnsbury, Newport, Silver Lake, Holden, and Verona--were at least 60 km (35 miles) inland, while the other six--Prospect Harbor, Brunswick, Wells, Rockport, Blue Hill, and Provincetown--were either on or within 10 km (6 miles) of the coast.

The Canadian Meteorological Office supplied records from a Draper anemoscope and data of pressure, temperature, humidity, and clouds at St. Hubert (30 meters), at Mt. St. Bruno (150 meters), and at Mt. St. Hilaire (400 meters) near Montreal, and Louiseville, north of Montreal.

Weather-conditions during eclipse of August 31, 1932 (S. P. Fergusson)--At 2 p.m. a Canadian cyclone of considerable intensity, central at The Pas at 8 a.m., had moved northeastward to northern Ontario and decreased in intensity, a weak secondary was central over New Jersey, and the Atlantic anti-cyclone had moved northward over West Virginia. Cloudiness had increased over the entire region east of the Mississippi Valley and temperatures were abnormally high. Contrasts of pressure were very small and winds continued light and variable.

At 5 p.m. the New Jersey cyclone had not increased in intensity but had expanded, covering the region between North Carolina and the St. Lawrence Valley; the Atlantic anticyclone was nearly stationary, covering West Virginia, western Pennsylvania, and Kentucky. The contrasts of pressure continued very slight, temperatures were high, and winds were light and variable throughout the eastern half of the country. The sky was cloudy or partly cloudy over New England and the coast as far south as Norfolk and west of the Mississippi Valley, where an anticyclone of slight intensity was moving from the west. Clear weather prevailed only over Maine, the Ohio Valley, and western Pennsylvania.

The relation between solar radiation and atmospheric temperature during the solar eclipse of 1932 (H. H. Kimball)--There were five stations equipped with Eppley pyrheliometers, mostly with Leeds and Northrup recorders. The sky at two of the stations was cloudy, at two partly cloudy, but with practically no direct solar radiation, and at one mostly clear. There were two stations with illuminometers, both clear, the data from which were converted into radiation-equivalents. A comparison of radiation with decrease of temperature indicated that for a decline of 0.60 gr cal/cm^2 the temperature decreased a median amount of 2°3 C (extremes 4°3 and 0°7). No measurement of net outgoing or "nocturnal" radiation was made; in previous eclipses Kimball in 1919 and Albrecht in 1927 found that this long-wave radiation was markedly higher during the time of totality than before or after.

The effect of the solar eclipse of August 31, 1932, on air-temperatures throughout the United States (Eleanor S. Brooks)--Clayton, 1905, summarized eclipse-effects on temperature: The fall begins 15 to 20 minutes after first contact; the minimum occurs from two or three to 20 minutes after totality; the lag is least in the free air, on mountains, and over the ocean, since the direct heating by radiation is here more important than the indirect; the return to normal temperature where the range is small comes at the end of the eclipse, elsewhere (over land-masses) one to one and one-half hours after the last contact; the amount of fall is 3° to 4°5 C over large land-areas, 1°8 over small islands, 0°9 over the ocean, and 0°6 at 300 meters over the ocean (kite-meteorograph); slight inversions have been noted at times. The large body of temperature-data obtained under great diversity of eclipse-amount, cloudiness, initial temperature, altitude, and exposure to water-bodies during the eclipse of 1932 have permitted a certain amount of statistical analysis. Within some 650 km (400 miles) of the central line of totality, where the obscuration was 90 per cent or more, the temperature-fall averaged 3°2 C in clear weather (67 stations), 2°2 in partly cloudy (27 stations), and 1°7 in cloudy (43 stations). From 650 to 1600 km (1000 miles) out, where the obscuration was 70 to 90 per cent, the temperature-falls for clear, partly cloudy, and cloudy were 2°1 (38 stations), 1°3 (12 stations), and 0°6 (2 stations). Beyond 1600 km and out to 40 per cent eclipse the temperature-depressions were 0°9 (17 stations), 0°9 (13 stations), and 0°5 (12 stations). The maximum eclipse-effect (with sling-psychrometer in open) was 5°6, though the greatest fall observed at any Blue Hill or Weather Bureau station was 3°9 C (with whirling or sling-psychrometer in shelter or shade).

The effect of altitude on the temperature-fall was, generally speaking, to reduce it. In the free air an airplane-ascent showed a lower temperature up to 1940 meters, but the change in the temperature was very slight above 700 meters. On Mt. Washington (1915 meters) no change of temperature was detected by the sling-psychrometer. The summit was in dense cloud throughout the eclipse. At Galehead (1160 meters) the eclipse-drop was but 2°0 C; at Gale River (about 430 meters) the eclipse-effect was 2°3. On Mt. Major (about 580 meters) the fall was 1°5 C, and at Alton Bay (about 190 meters) near its base the fall was 2°5 C. In more nearly vertical relationship, the temperature-changes on office building and ground at Columbus, Ohio, were 1°8 and 2°5 C, and at Buffalo, 1°7 and 2°8 C, while at top and base of the Pilgrim Monument, Provincetown, 80 meters high, the falls were 2°1 and 2°6 C, respectively.

The time of minimum temperature at Harvard stations was from seven minutes before to 14 minutes after totality, with a mean of four after; at Weather Bureau stations the minimum was seven to 23 minutes after the maximum eclipse, with a mean of 14 minutes.

Moisture-phenomena during an eclipse (Eleanor S. Brooks)--The change in relative humidity is largely the inverse of the temperature, averaging from four per cent, where the temperature-change is 1°4 C, to ten per cent, where the change is 3°4 C. Changes in vapor-pressure are quite diverse, but on the average there is a rise of 0.01 inch, as convection dies down, allowing moisture evaporating from the surface to accumulate in the lower air.

Changes of pressure and wind during an eclipse (S. P. Fergusson, Charles F. Brooks, and Eleanor S. Brooks)--Pressure-changes observed heretofore have been very small, so small that, as residuals after elimination of cyclonic changes, diurnal changes, and irregular small-scale fluctuations, their existence has been open to question. There has appeared to be a tendency to a maximum at or shortly after the eclipse-maximum, and possibly slight minima before and after this. Our new data, however, with open-scale instruments, do not indicate any eclipse pressure-pattern, and the fluctuations on the day of the eclipse were of no greater size than those on the previous day.

If there are pressure-changes induced by the cooling effect of the eclipse, an eclipse-wind might be expected. It can be found, however, only after subtracting (1) any progressive change, (2) any reduction in velocity and change in direction due to decreased convection, and (3) any local winds due to the cooling, such as air-drainage or a land-breeze. The chances of success are almost nil. Nevertheless, with data from a large number of stations, statistical process will eliminate (1) and (3) and will show the amount of (2), thereby leaving it possible to detect the presence of whatever eclipse-wind there may be. The Indian eclipse of January, 1898, occurred under such nearly perfect meteorological circumstances--cloudless skies, light winds, and high Sun--and with so many stations (155) observing, that it should indicate an eclipse-wind if any could. So the wind-changes at the 98 cloudless stations were analyzed for convectional change in direction as well as for the well-known decrease in velocity and also for a change in direction which might be expected from a tendency of air to flow outward from the central line of totality. Though 72 per cent of the stations showed the characteristic convectional decrease and then increase in wind-velocity and 40 per cent had a central period of calm, there was no systematic change in direction to the left with decreasing wind and to the right with increasing wind, as would be expected from the decrease and then increase in the deflective effect of the Earth's rotation. However, initial wind-velocities were generally low and the latitude low; consequently deflection could not be large. With the possible convectional change in direction not in evidence, the way was easier to discover an eclipse turning, if any. In the zone out to 500 km (300 miles), containing 61 stations, the wind turned as an eclipse-effect required at 35 per cent of the stations and turned opposite to an eclipse-wind at 19 per cent, there being calms or no change in direction at 46 per cent. In the zones from 500 to 1500 km (950 miles) from the central line, including 33 cloudless stations, there was an eclipse-turn at 23 per cent, an anti-eclipse turn at 21 per cent, and calm or no change at 56 per cent. The United States morning eclipse of 1900 had a decrease and then an increase in velocity at 44 per cent of the 68 stations, while 15 per cent more showed no change as the eclipse came on and an increase later. The East Indian eclipse of 1901 showed no consistent eclipse-pattern. In the 1932 eclipse there was a marked convectional fall and rise in wind-velocity, 62 per cent of the 106 stations where eclipse was 90 per cent or more showing this. There was also a convectional turning in directions at 22 per cent of 104 stations and an anti-convectional turning at 28 per cent, while 50 of the stations in the zone of 90 per cent or more eclipse showed no change. No eclipse-wind in 1932 is apparent statistically, though at the pilot-balloon stations there is a suggestion of an inflow above and an outflow below from the clear area on the left of the shadow-path.

Cloud-changes during an eclipse--Many astronomical eclipse-expeditions have almost "miraculously" got photographs of the totally eclipsed Sun when low-hanging dense clouds broke away just in time, and closed in again shortly afterwards. When we remember, however, that these low clouds are usually the result of convection during daylight, it is not surprising that they break away when the sunlight is shut off. When the sky is not cloudy it is a matter of common observation that cumulus clouds decrease as the eclipse comes on and increase again as it passes off. In the eclipse of 1932 the changes in low cloudiness at 160 stations where the eclipse was 70 per cent or more were tabulated. At 81 per cent of the stations with under 0.4 of low cloudiness there was a decrease as the eclipse came on and at only seven per cent an increase. The corresponding figures for partly cloudy (0.4 to 0.7) and cloudy (0.8 to 1.0) were 64 per cent against 29 per cent and 29 per cent against 11 per cent. After totality, which was already mid or late afternoon, an increase of low cloudiness occurred only under the most favorable circumstances, namely, where the humidity was high enough to maintain low clouds throughout the eclipse, yet not so high as to keep such an extensive cover as to prevent the returning sunshine from warming the ground. So, of the partly cloudy stations 58 per cent had an increase after totality and 36 per cent had a decrease; at clear stations, 29 per cent increased and 31 per cent decreased, and at the cloudy ones 21 per cent increased and 21 per cent decreased.

Middle and high clouds could be considered only where there were so few low clouds that a reliable estimate could be made of the extent of the high clouds. At 66 stations where the eclipse was 70 per cent or more there seemed to be no consistent effect of the eclipse on the extent of middle and high cloudiness. Perhaps this should have been expected in view of the absence of change in temperature above a height of 1900 meters, or under the heights of the clouds involved. The percentages of stations showing increase and decrease in middle and high cloudiness before the maximum of the eclipse were 39 and 41 per cent, and after the maximum 37 and 38 per cent.

Shadow-bands--Shadow-bands were observed at only a few stations. Of most interest were the successive series seen by H. H. Clayton at Rockport as the strip of light narrowed. First, there were large waves, evidently related to the varying refraction in the lowest air-layers, then came somewhat smaller ones, and finally a sharper set moving with the same direction and velocity and having the same wave-length as the alto-cumulus clouds. Shadow-bands were observed by R. L. Feldman near Washington, D. C., where the magnitude of the eclipse was 89 per cent.

Aerological observations during the total solar eclipse of August 31, 1932 (Jerome Namias, C. H. Pierce, and H. Wexler)--Pilot-balloons were released at frequent intervals from four stations, two of which were near the center of the eclipse-path and the other two at opposite margins of the zone of totality. At only one were two theodolites used. The results at this station from a single theodolite would have been so close to those obtained with the two theodolites that it seems fair to assume satisfactory accuracy for the stations having only one theodolite. The Massachusetts Institute of Technology, and Maine Coast Artillery, and the United States Naval Observatory cooperated. At all stations during the afternoon there was a southerly wind at low levels which shifted sharply to northwest at about 1600 meters. The balloon-run made after totality at the stations near the center of totality--Cape Elizabeth and Limerick--show the same wind-direction, level for level, that prevailed before the eclipse. Concord, on the western margin, shows a marked shift to southerly before to easterly after totality at low levels, yielding an outflow from the shadow, and a shift toward west at higher altitudes, indicating an inflow overhead. Boston, on the same side of the path, showed no marked changes. Brunswick had a noticeable shift from south to southwest at low levels, indicating an outflow, followed by a shift toward south at higher altitudes, giving an inflow at the same altitude as at Concord.

By subtracting vectors representing wind-direction and velocity at the same altitudes before and after totality at Limerick, Concord, and Brunswick, vectors were found which showed the changes in air-movement which may be ascribed in part to the eclipse. Vectors at Concord are directed outward from the path of totality up to 1600 meters, after which vectors show a general inflow. At Brunswick, on the other side of the path, vectors are directed outward from the path of totality up to 680 meters; from there up to 3700 meters they point inward. Vectors at Limerick show a general flow parallel to the path of totality from the ground to 3700 meters, but with increased speed from the direction of the shadow after it had passed.

With the exception of a few discrepancies, observations seem to agree well with the theoretical calculation of air-movement during an eclipse; that is to say, the observed cooling-effect of the eclipse with the consequent sinking of the isobaric surfaces would result in an inflow aloft and an outflow at lower elevations across the boundaries of the path of totality and a movement parallel to the path at the center.

An airplane-flight by Dr. Irving Langmuir, carrying a Bosch and Bosch meteorograph loaned by the Massachusetts Institute of Technology, started at Concord shortly after the eclipse began and ended there soon after the shadow had passed. The ascent, therefore, represents practically uninfluenced conditions and the descent nearly the maximum of the eclipse-effect. The record shows that the cooling effect under the particular conditions extended definitely to about 700 meters above the surface and in slight degree to 1940 meters, though it is speculative how much of this cooling can be attributed to the eclipse. The specific humidity increased in the surface-layers. A stratus haze-layer sank about 180 meters, probably due largely to the effect of decreasing irradiation during the eclipse. If there was any sinking of air in the upper layers it must have been quite inappreciable and therefore not detectable by present-day aerological methods.

Theoretical remarks about the meteorological effects of a solar eclipse (B. Haurwitz)--The radiant energy received from the Sun during an eclipse can be assumed to be roughly proportional to the unobscured part of the Sun. Since only the total radiation from Sun and sky on a horizontal surface was measured it does not seem necessary to take into account the decreasing brightness towards the solar limb and possible changes of atmospheric turbidity during the time of the eclipse. The radiation on a horizontal plane is further dependent on the zenith-distance of the Sun. With an atmospheric transmission-coefficient of 0.6 good agreement is obtained between the observed and computed range of the radiant energy. The radiation begins to fall off again before the fourth contact, since the increase of the zenith-distance of the Sun then becomes more influential than the increase in visible area of the Sun.

The decrease of solar radiation during totality causes a temperature-drop. The time of the minimum of temperature occurs most closely to the time of totality at the surface of the Earth. Higher up the time of minimum of temperature is retarded and the amount of the temperature-drop decreases, as follows from the theory of conduction of heat. With plausible values for the conduction-coefficients we obtain a time-lag of 15 minutes, in agreement with the observations.

Since the decrease of the temperature is small the pressure-change must be small, too. It is estimated that the upper limit of the pressure-change would be 1 mb (0.03 inch), but this value is probably too large. It seems highly improbable that such pressure-changes could be detected and separated from the pressure-changes due to other causes. In agreement with these considerations no definite change in pressure was observed.

With the above-mentioned value for the pressure-change it is possible to compute an upper limit for the pressure-gradient. The velocity of the Moon's shadow was about 4.8 km/min, the time from the first contact to totality was 70 minutes, so that the pressure-change of 1 mb should be spread out over more than 3000 km. But even if we choose instead of this only 100 km the corresponding gradient-velecity would only be about 1 m/sec. Such a value can hardly be found in the wind-records among the other fluctuations of the wind. In addition we have to take into consideration that gradient-wind exists only under steady conditions. Since the eclipse-phenomenon travels with a speed of 4.8 km/min we cannot expect that the gradient-wind relation holds in this case. The influence of surface-friction would further diminish the intensity of eclipse-winds.

It has been found frequently, during the last eclipse by S. P. Fergusson, that the wind goes down during totality. This can be explained as an effect of the diminished thermal convection when the solar radiation is cut off more or less completely.

Suggestions for further studies (B. Haurwitz and C. F. Brooks)--In connection with this theoretical discussion some suggestions offer themselves for the work during future eclipses. The radiation should be measured as accurately as possible and also with color-filters in order to discover probable variations of atmospheric turbidity which might be caused by slight condensation-phenomena. Very interesting are observations of sky-polarization, especially if it would be possible to determine the sky-polarization at a great number of points during a short interval of time. Measurements of the outgoing radiation are much needed. For the interpretation of the air-temperature variations the temperature at the Earth's surface should be measured and the specific heat and conductivity of the ground should be determined. The air-temperature should be measured, or still better, recorded at a great number of heights in order to study the propagation of the cooling upwards. Of special interest would be observations at two neighboring stations at the same level over solid ground and over water. In a similar fashion to the temperature, the humidity and wind should be measured or recorded at a number of heights (say 0.5, 2, 5, 10, 20, 35, and 50 meters). The humidity-measurements would be particularly important for the study of temperature-changes since the moisture-content affects the radiative transfer of heat. Steel structures like radio masts seem very suitable for such observations. Pilot-balloon ascents will be useful if double-theodolite stations can be provided. If a number of stations can be manned, at least five stations along the path of the eclipse should be installed, 500 and 200 km from the zone of totality.

The atmospheric pressure should be measured at every station to discover small pressure-changes due to the eclipse, preferably with mercurial barographs of wide bore and open scale or with sensitive aneroids kept at constant temperature. The cloudiness could best be recorded by frequent photographs (every five minutes or oftener). The cloud-motions should be observed continuously with the nephoscope.

Finally, the direction and position of shadow-bands should be observed, as during previous eclipses.

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MEASUREMENTS WITH A CLIMATOLOGICAL ULTRA-VIOLET DOSIMETER IN CENTRAL PENNSYLVANIA

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The simple instrument with which the measurements presented in this paper were made has been described in several papers by Weyde and Frankenburger ([see 1 of "References" at end of paper] and others elsewhere. It may be just stated that it consists mainly of a test-tube with a liquid coloring red under the influence of that part of the ultra-violet spectrum which produces the erythema and which is therefore of particular biological importance. The color of the liquid is compared with a standardized color-wedge that gives units of radiation which are calibrated against erythema-doses. The instrument is not only cheap but also easy to handle and to carry. There exist as yet only a few series of observations, the most important of which have been conducted by Knepple [2] and Ungenheuer [3] at Oberstdorf, Bavaria, Germany, in the high mountains, by Bossolasco [4] during the International Polar Year at Mogadiscio, Italian Somaliland, Africa, and by Fuchs [5] on an expedition through south-central Europe.

During the year 1934-35 about 140 measurements were made at the Pennsylvania State College, most of them in the early afternoon hours (14 o'clock) on fair, sunny days where the clouds did not exceed 0.2. The observations were well distributed over all the seasons. Under the general conditions of elevation (371 meters = 1217 feet) and locality it could not be expected that the ultra-violet radiation could match the intensities observed in the high mountains. The maximum value attained was 27.8 dosimeter-units, which means that the time to produce an erythema (first sign of sunburn) would be about 32 minutes. This value was measured on several occasions during July and August, while the lowest value of 0.61 dosimeter-unit was measured in December, which means theoretically that an exposure of at least three hours would be necessary to produce erythema. This is, however, only merely theoretical as a minimum value of about ten dosimeter-units is required to get an active response from the skin. The average of all measurements gave a value of 13.5 dosimeter-units corresponding to 66 minutes as necessary dose for erythema.

All our measurements as well as those of the previous investigators show that the largest influence on the ultra-violet radiation is the altitude of the Sun above the horizon. This is not only true within the single day but also for the variation of solar altitude during the seasons. For total radiation we refer in this respect to the work done by Kimball[6].

Table 1 shows the connection between solar altitude and ultra-violet intensities. The values correspond rather closely to the ones found by Ungeheuer [3] in the Alps, and it can be stated that in the winter months even under the best circumstances only about one-fifth of the ultra-violet radiation can be expected that is normally obtained in summer due to the low solar altitude. This can, however, be partly compensated by the presence of a snow-cover which reflects a large amount of ultra-violet. An attempt has been made to correlate the ultra-violet radiation with the meteorological elements. For accurate measurements with the best of physical equipment reference is made to the excellent studies by Coblentz and Stair [7]. Of particular interest is the influence of the suspended matter in the air, that is, the loss of ultra-violet light due to the absorption of impurities. It cannot be stated which part of the aerosol is mainly responsible for this absorption but it is a matter of experience that all the impurities vary about in the same way. Therefore, it seems allowable to choose one element as representative of these impurities. Since regular counts of the condensation-nuclei were made at our station the coinciding ultra-violet measurements were compared with this element of the aerosol. The result is to be seen from Table 2. This table shows the definite trend of decreasing ultra-violet intensity with increasing nuclear contents. It might be said that this is due to the annual variation of the impurities with a maximum in winter, a minimum in summer [8], consequently this result as indirectly due to the low solar altitude in winter and concurrently high nuclear contents. However, it may be stated that most of our measurements in winter occurred in polar or modified polar air-masses, which are relatively low in nuclear contents. Therefore, one can conclude that the amount of impurities in the air as represented by the condensation-nuclei is an additional and important factor as concerns the absorption of the biologically important radiation.

Table 1--Solar altitude and ultra-violet intensities

Solar altitude	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°	60°-70°
Ultra-violet dosimeter-units	1.41	4.86	8.58	13.86	17.60	23.62

Table 2--Condensation-nuclei and ultra-violet measurements

Condensation-nuclei in 10^3/cc	0-10	10-20	20-30	30-50	50-100	>100
Ultra-violet dosimeter-units	21.78	14.65	14.21	11.02	9.81	7.87

Another simple test for a certain type of turbidity in the air is the scale of sky-blue by Linke and Ostwald. The sky-blue was estimated with such a scale simultaneously with the ultra-violet measurements and the relations are given in Table 3. The sky-blue is a good indication of the scattering that occurs in the air and except for the last value of very deep-blue sky the ultra-violet decreases with increasing blue. Knepple [2] has shown that the ultra-violet sky-radiation amounts to 20 per cent at noon and up to 50 per cent of the total ultra-violet radiation early in the morning and the evening. As the low values of sky-blue indicate only a large scattering of the short wave-length of the spectrum the amount of ultra-violet radiation from the sky that benefits the dosimeter has to increase, too. The shape of the instrument does not permit one to discriminate accurately between direct solar and scattered sky-radiation.

Table 3--Sky-blue and ultra-violet measurements

Sky-blue scale-division	4	5	6	7	8	9	10
Ultra-violet dosimeter-units	24.70	20.60	14.97	14.18	9.20	8.70	11.13

The influence of the air-mass on the ultra-violet radiation can only be discussed very generally as the number of observations is not sufficient to permit a survey of the different seasons. For the same reason only four types of air-masses have been used with the corresponding ultra-violet radiation as shown in Table 4. Tropical air-masses of all kinds, which occur in this region principally in summer, show the highest average although they are still far be-

Table 4--Air mass and ultra-violet measurements

Air-mass	T	P	Np	I
Ultra-violet dosimeter-units	13.97	13.10	12.80	11.85

maximum values in summer of 27 units, all occurring in connection with polar air. The polar and modified polar air-masses which rank below the tropical air are mainly due in this place to their particularly frequent occurrence in winter. The lowest average radiation is to be observed in indifferent air-masses, which have been stagnant over the place of observation for a longer period and have accumulated a large amount of suspended impurities.

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PILOT-BALLOON OBSERVATIONS AT SEA

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Due to the conflicting opinions which exist on the feasibility of these observations and the increasing demand for information as to existing upper-air winds over oceanic areas, the following discussion and suggestions are presented in the effort to shed further light on the problem so arising.

First, the attempt has been made to obtain as much information on the question from the results which have already been secured as is possible. A summary of these results was made as a project of the Civil Works Administration during the early part of 1934, which summary included all the data that were available up until the spring of that year. With one notable exception, the summary includes practically all of the results for the observations which had been taken up until, roughly speaking, the end of 1933. The exception mentioned is that the results of the observations which had been taken by Great Britain were omitted. This omission was due to the fact that that country was planning to make a similar summary at that time and the data were therefore withheld. Using the data from the project of the Civil Works Administration, a tabulation has been made of the number of observations which have been secured at 500-, 1000-, 2000-, 3000-, and 4000-meter levels by five-degree squares for the oceanic areas of the Northern Hemisphere.

Figures 1 and 2 show the results of this tabulation for the summer months--June, July, and August. In these figures, the numerals in the upper right-hand corner of a square give the number of observations at the 500-meter level, those in the lower right-hand corner give the number of observations at the 1000-meter level, and, continuing around counter-clockwise, there is given, in succession, the number of observations at the 2000- and 3000-meter levels, respectively, with the number of observations at the 4000-meter level in the center. The cases in which the number of observations at 4000 meters were equal to, or greater than, one-half the number of observations at 500 meters are indicated by a circle around the center figure.

The agencies or organizations which took the observations were divided into the following four groups: (1) German scientific expeditions; (2) German merchant marine; (3) the United States Navy; (4) other scientific projects other than German. The letter G is used to denote that the observations shown were participated in by the German scientific expeditions, the letter M is used to designate participation by the German merchant marine, the letter N is used to denote United States Navy observations, and the letter R is used to denote observations secured by the remaining organizations. A circle around any of these letters indicates that at least one observation of maximum height greater than 10,000 meters was secured by that group.

The R-group includes (1) observations taken by the personnel of the yacht Carnegie, (2) observations taken by the United States Weather Bureau personnel aboard the Dollar Line steamships in cooperation with the United States Navy, (3) observations taken by the Italians, and (4) the original sextant-observations made by De Bort and Rotch during the years 1905 to 1907.

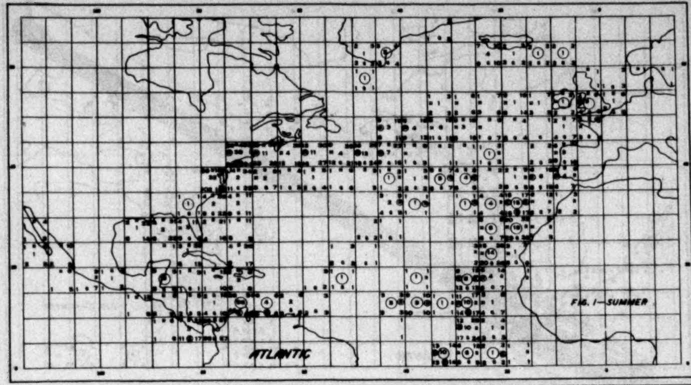

FIG. 1—SUMMER

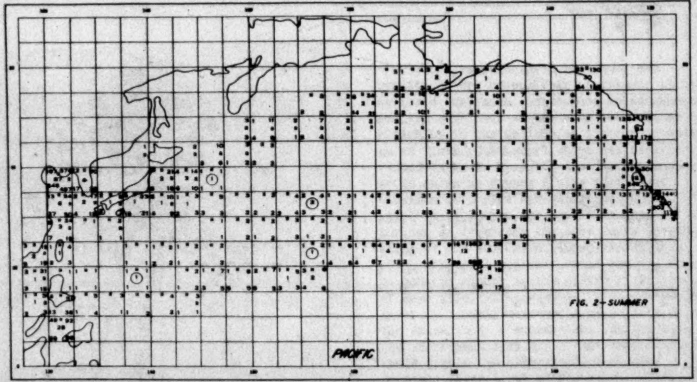

FIG. 2—SUMMER

It will be seen that the encircled M's and R's predominate. The long observations for the R-class were secured almost entirely by the De Bort and Rotch expeditions. The ships which were used by them had an average displacement of about 500 tons which is in marked contrast to the displacement of the ships used, for instance, by the United States Navy and the German merchant marine. The tonnages of these ships range usually between 10,000 and 30,000 tons, roughly speaking. This would seem to indicate, off-hand, that the weight of the ship does not seem to play much of a part in determining the length of the observations secured. It must be remembered, however, that expeditions such as the one named have a better chance to select the conditions under which they attempt to take observations since the observations are taken for the sake of observations themselves instead of, as is generally the case with the Navy, taking them to meet the immediate demands of aeronautical operations. Also, the aerographers in the Navy frequently abandon these observations due to the pressure of other duties, whereas this is not the case on expeditions of a scientific nature. For these reasons, then, no comparison can properly be made between the results obtained by the Navy and those obtained by other agencies. In the absence of the tabulation of sea-conditions by those agencies obtaining the long runs, neither can any conclusions as to the frequency of the possibility of obtaining such runs be drawn. It will further be noted that the number of observations at the higher elevations decrease rapidly with increasing latitude. Generally speaking, the higher the latitude, the greater the

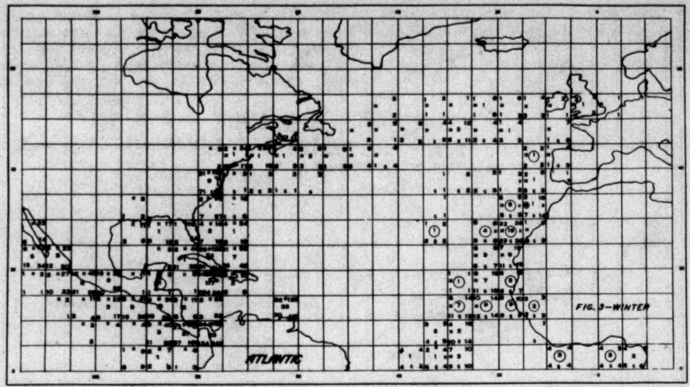

FIG. 3-WINTER

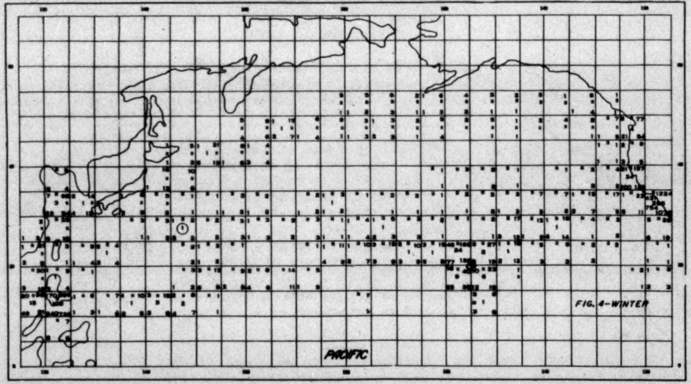

FIG. 4-WINTER

frequency of low cloud-occurrence and the rougher the average sea-conditions. This is explained by the prevalence of large high-pressure areas in southern latitudes and the situation of the mean storm-track to the north of these areas. Figures 3 and 4 show the results of the corresponding tabulation for the winter. The effects of the seasonal shift of the mean storm-track are quite evident here.

Regardless of the results which have been obtained so far along these lines, it is believed that there are certain improvements in procedure and additions of equipment which, if adopted, will produce results which will help considerably to insure the practicability of the taking of these observations.

One of the simplest things to be considered is that of increasing the size of the balloons. Such a procedure would be doubly beneficial in that it would increase the size of the image to be followed in addition to enabling the balloon to attain a much greater height while the ship travels any given distance from the point of the balloon's release. The practice of using large balloons is followed by the Germans, and, notwithstanding the rather cumbersome type of theodolite used, the results secured are, generally speaking, superior to those which have been obtained by American methods.

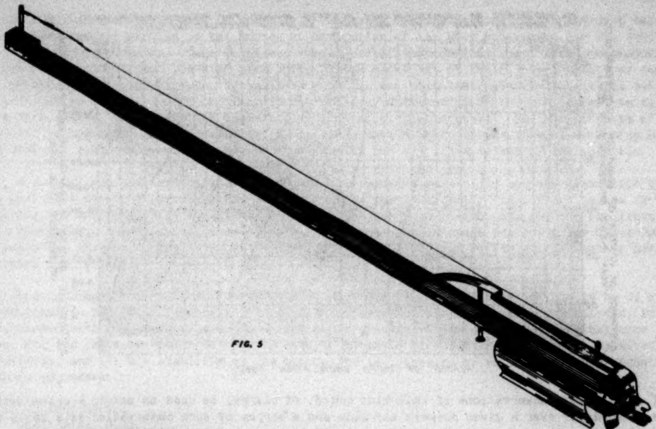

FIG. 5

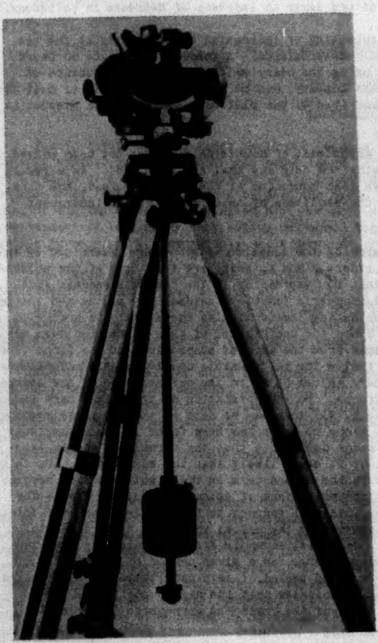

FIG. 6

In regions in which low cloudiness conditions are excessively prevalent, it is believed that much can be done to compensate for the shortness of the runs obtained by attaching to the balloon an instrument known as an "inversion-meter" which has been invented by A. H. Mears of the Weather Bureau. As is shown by Figure 5, the instrument consists of a fine wire stretched on a light frame. When the apparatus ascends through an inversion the more rapid lengthening of the fine wire causes the closing of an electrical circuit which can, in turn, be made to result in the giving of a signal of some kind. Since the top of a low cloud-layer is usually determined by an inversion, the emission of a sound-signal at the time the instrument encounters such an inversion would enable the determination of the probable upper limit of the cloud-layer. A

$$\theta_0^2 = \frac{\Phi^2 H^2 p^4}{(\lambda p^2 - g)^2} - \frac{\lambda L^2}{K^2 g p^2}\left[\frac{\sin^2 \frac{\pi}{p}\sqrt{\frac{g}{\lambda}}}{\left(1+\cos\frac{\pi}{p}\sqrt{\frac{g}{\lambda}}\right)^2}\right]$$

θ_0	*Amplitude of oscillation of theodolite with respect to the vertical (radians)*
Φ	*Amplitude of ships oscillation (radians)*
H	*Distance of point of suspension from the axis of the ships oscillation*
p	*2π divided by the oscillation period of the ship*
λ	*Length of the equivalent simple pendulum*
g	*Acceleration of gravity*
L	*Torque due to friction in gimbal bearings*
K	*Moment of inertia of theodolite proper*

FIG. 7

ADJUSTMENTS OF COUNTERBALANCE PLOTTED AGAINST THE PERIODS FOR WHICH THE NEGATIVE TERM OF THE AMPLITUDE EQUATION BECOMES INFINITE.

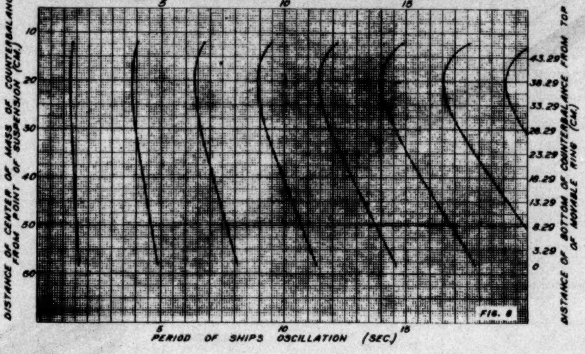

FIG. 8

set of simultaneous observations of this kind could, of course, be used to obtain a cross-section of the cloud-layer over a given oceanic air-line and a series of such observation-sets could be used to determine the extent of the tendency of the layer to increase or decrease in thickness.

There is finally to be considered the possibility of increasing the stability of the theodolite by making the proper adjustment of its counterbalance. A theodolite for use on board ship is shown in Figure 6, the counterbalance being the heavy weight which on instruments of this kind, manufactured by the Keuffel and Esser Company, can be adjusted vertically to suit the various periods of oscillation which may be described by the platform upon which the theodolite is set up.

As far as can be learned, the problem of adjustment of counterbalance has not been solved heretofore, the method of "trial and error" being the only one that has been used. As a result of recent theoretical investigations which have been conducted at the Weather Bureau, the formula as shown in Figure 7 has been derived for the amplitude of oscillation of the instrument with respect to the vertical.

All of the quantities on the right-hand side of the equation (Fig. 7) are determined by the conditions under which the instrument is used except K and λ, which are functions of the adjustment of the counterbalance. It will be seen that the expression in the brackets becomes indeterminate when the coefficient of π in the trigonometric functions assumes any of the odd integers as a value. An application of the rule for evaluating indeterminates shows that the bracketed expression becomes infinite at these points. Since the coefficient of this expression does not vanish for finite distances of the counterbalance from the axis of suspension and the first term on the left-hand side of the equation remains finite for all possible counterbalance-adjustments, it will be seen that this formula gives imaginary values of θ_0 in the neighborhood of the points for which the bracketed expression becomes infinite. No interpretation of these imaginary values has been found until the present and, as a result, all that can be said is that in these regions at least, the formula does not hold. However, since no error has been found in the assumptions made or in the methods of derivation used, it seems improbable that the formula is wholly inapplicable. If, then, it does hold for any region, it seems likely that the minima of θ_0 are to be found in the neighborhood of the points for which the second term on the right-hand side becomes infinite. This follows from the probability that the regions of coincidence of the curves for the actual θ_0 and the theoretical θ_0 are symmetrical with respect to these points, and the intuitionally evident probability that the curve representing the actual values of θ_0 is a smooth, continuous one. Assuming this to be the case, the curves shown in Figure 8 have been computed as being those to be used in adjusting the counterbalance for a given period of oscillation of the ship. In the cases where the ordinate for a given period of ship-oscillation is intersected by the curves in more than one place, the formula indicates that the higher position of the counterbalance should be used since the coefficient of the bracketed expression is larger for these positions.

Two possibilities exist in the way of a test for the results of these calculations. One is to set the instrument upon what is known as a "Scoresby testing-machine" which has been designed by the Gyro-Compass Section of the Bureau of Navigation of the Navy Department for the purpose of testing gyro-compasses. This machine produces oscillatory motions about axes corresponding to the roll-, pitch-, and yaw-axes of a ship. These machines, in their present state of design, do not furnish the correct type of oscillatory motion for this test, however, since the period of oscillation for one direction of motion is entirely different from the period for the opposite direction of motion and the oscillations are not simple harmonic. The correct type of motion can be secured by a change of design of the connecting rod for the driving mechanism and the Scoresby platform, however, and such a change is not one which is out of the question.

A second, but less effective, test of the calculations made is to set the theodolite up on the deck of a ship and correlate the oscillations of the instrument with respect to the vertical with (1) the counterbalance adjustment used, (2) the observed period, and (3) the amplitude of roll occurring. These tests are being made at present by Lieutenant Graves of the Coast Guard on board the vessels of the International Ice-Patrol, and Mr. Van Patten of the Weather Bureau on board the vessels of the Matson Line.

Considering, then, that the United States Navy has found these observations to be of sufficient value to take them regularly without the improvements in procedure just mentioned, it is not, consequently, an exaggeration to assert their practicability when (1) larger balloons are used, (2) the inversion-meter is used to obtain thickness of cloud in regions of excessively low cloudiness, and (3) the stability of the theodolite is increased by making the proper counterbalance adjustment.

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A PRELIMINARY SUMMARY OF THE MULTANOVSKI SCHOOL OF LONG-RANGE WEATHER-FORECASTING

Irving I. Schell

Introduction

The Institute of Long-Range Weather Forecasts, since 1930 a full fledged division of the Central Weather Bureau of USSR, was established in 1912, at the Central Geophysical Observatory as a result of a resolution adopted at the Second Meteorological Congress, calling for the development of forecasting methods to meet the needs of agriculture. B. P. Multanovski, present head of the Institute was entrusted with the work of carrying on investigations to promote the development of long-range forecasting methods. Together with his associates he developed, in the course of many years, the methods which serve at present as the basis for forecasts.

The first regular forecasts for 10-14 days to 2-3 months in advance began to be issued by Multanovski in 1920. They were of an experimental nature. In time they proved so successful that since 1932 they are being issued in the same manner as the regular short-range forecasts. The forecasts are now also extended for longer periods in advance. Under certain conditions they are issued for as much as five months ahead.

The time-interval for which the forecast is generally issued is not determined by calendar periods, weeks, months, seasons, but by the period which marks the type of synoptic process involved. Inasmuch as the development of a synoptic process often varies with season, and from season to season and in addition is a function of a number of synoptic factors, the time-interval must necessarily vary too, and consequently the period for which the forecast is issued. A monthly forecast, let say, may therefore embrace portions of two calendar months and sometimes less than one.

It will not be attempted here to present a complete analysis of the methods of attack as well as of the actual technique of the Multanovski School for the reason that, to quote a collaborator of that School, no exposition of these has ever been made in print. This is incidentally true of short-range forecasts as well. For although it is possible to present the fundamental principles of synoptic meteorology it is impossible to present and teach the technique of long- and short-range forecasts based on it. This can be learned only independently, by working under a competent person in the Weather Bureau. However a fairly adequate presentation of the methods is made possible from a study of a number of investigations in which these methods were employed and several publications in which they were described. Some oral information also proved helpful. Of the three available papers in which exposition of the principles and methods is attempted the one by Prof. Tichomirov contains the briefest and simplest, and will be followed here (see bibliography).

A synoptic process can be studied either statistically, implying a determination of the necessary and sufficient statistical indications for any synoptic situation which precedes the investigated process, and a determination of the necessary conditions which accompany the synoptic phenomenon; or by the kinematic method which is a study of the form and direction of the trajectories of special points; or dynamically, which involves a determination of the time-space relationship between the trajectories of the combined properties, characterizing the process, and the explanation of these relationships, if possible, by study of the physical mechanism. The Multanovski School utilizes all three forms of analysis.

The method is known best by the name of composite-map method. It differs from time-space correlation long-range forecasting methods and most others in that it is based on classical synoptic considerations. (An attempt has also been made to show that it has a frontological basis as well and thus to show the synthesis between the Multanovski and Norwegian schools of Meteorology.)

I--Background

It is to the credit of Multanovski that the concept which later became known as the air-mass concept was recognized by him when he first started his investigations nearly 25 years ago. It was a bold hypothesis and he drew conclusions which, as shown by his results and those of others, were justified.

Multanovski considered the notion of the weather moving from west to east along with the general circulation--a notion prevalent at that time--as untrue. He believed that the weather was "made," at least in part, in the north in sub-polar regions. This basic and natural idea served as the foundation for the methods which he developed. Multanovski's reasoning, which is simple, was more or less as follows.

In sub-polar regions are found strong accumulations of heavy cold air. For reasons as yet not completely understood, lumps or masses of air separate from these regions every now and then. If one can determine the places from which these air-masses or "tongues" of air start and the paths along which they travel, one can naturally draw corresponding conclusions regarding the weather in the region over which these air-masses travel. One can also draw conclusions regarding the weather in adjoining regions, since the weather in the latter is determined to a large extent by that in the region occupied by the air-mass.

At present, when sub-polar regions have ceased to be a blank space on the map, and we are able by availing ourselves of the existing surface and upper-air observations, to follow the movement of the air-masses, the above-mentioned scheme appears very natural. However, when Multanovski set to work, a great deal of intuition and caution was required in the utilization of this idea, for there were very scant observations and it was not possible to check these basic assumptions. One could judge the correctness of the whole scheme but indirectly. Multanovski's approach to the working out of his hypothesis was quite ingenious.

At one time the classification of trajectories of areas of high and low pressure and construction of means seemed quite promising and a great deal was expected from the work in that direction. Detailed investigations, however, gave disappointing results. It soon appeared that the minima do not take any favorite path. Furthermore, the variations were so great that mean paths gave nothing. The same was true for maxima. In fact, it was even worse, for it was found that they change paths even oftener, although this was not true everywhere. Other classifications also proved fruitless. An attempt to classify the trajectories according to months (early issues of Monthly Weather Review) failed to alter the complexity of the problem. Indeed, Sir Napier Shaw was moved to remark (Forecasting the weather, p. 513, 2nd edition) that "No path can be drawn so tortuous and so out of the way that we can fairly say that it must be ruled out as a possible path for the center of a cyclonic depression."

It occurred to Multanovski that perhaps the complexity exhibited by the map on which the trajectories, even for a single season, were plotted might be due to the fact that they represent trajectories of pressure-areas of different origins and hence, if grouped according to their origin or in some other manner, the picture might become much simpler.

Another happy thought of Multanovski was to choose for his experiment the trajectories of the maxima. His reasoning was that the central part of a maximum forms, at any rate as a first approximation, the nucleus of high pressure, and therefore the trajectory of the maximum can be taken as a first approximation as the trajectory of the nucleus, in other words, the trajectory of the air-mass. Such a choice seemed to him to be more reasonable, for in dealing with anticlones he had a more concrete subject than would be the case with cyclones. He was moved to his choice partly because of the idea prevalent in the earlier part of the century, an idea advanced by Hildebrand-Hildebrandsson, that an anticyclone "directs the weather."

In studying the trajectories of anticyclones Multanovski had actually studied the movement of air-masses and to a certain extent employed methods of air-mass analysis. It will be seen later than in his analysis he employed fronts as well, though not in the sense known today.

II--Facts and principles of forecasting

In grouping the trajectories according to their origin Multanovski started from the following consideration. All maxima which enter Europe move from the west with the general circulation, provided there is no intrusion of nuclei of high pressure from sub-polar regions (no polar influence). The effect of such an intrusion would be to endow the direction of the maximum with a meridional component. He also found that some of the trajectories had a component, directed from east to west, or opposite to the prevailing circulation. He thus obtained three groups, one directed from the west, the second from the northwest quadrant, and the third from the northeast quadrant. He then set these on separate maps. In doing so he actually traced, as will be seen later, very closely the origin of the air-masses.

In examining the tracks of each individual maximum for a period of many years he discovered that in general the intrusion of maxima takes place along definite paths and that the tracks are concentrated, for the most part, in definite zones. These concentrations were selected and a single average axis called a median or normal was determined for each. Thus there was obtained a sort of skeleton or fan representing average trajectories which can be regarded as the typical positions of the tracks of maxima. It also appeared that the axes with a northerly component formed two distinct groups or fans, the point of intersection of the axes of the first group, center of fan, lying in the Arctic at 105° west and 86° north and the other around Taimir (northwestern Siberia). The axes of the first group represented maxima entering Europe from the northwest, and were called the normal polar type, while the other fan represented average tracks of maxima moving into European Russia from the northeast (in winter also from the east) and were named the ultra-polar type. The anticyclones arriving from the west, region of the Azores, followed a rather narrow zone, almost straight east, and was called the Azores normal. In addition to the main Azores group there are a few offshoots directed northeastward.

The positions of axes over certain regions calls for a completely determined type of weather in corresponding regions, so that a frequent repetition of the same type of weather gives a definite stamp to that region. Since there is associated with each axis a certain type of weather, and a normal type of weather corresponds to each normal, it should follow that the axis should therefore reflect the actual conditions occurring in nature. For evidence of this and the reality of axes we can turn to the distribution of tree-types. We should expect to find the total of favorable and unfavorable factors, among them the meteorological, reflected in the growth of every plant, but especially of a tree since it grows for many years. In this way the distribution of definite tree-types offers a real picture not only of the climate but also of the weather of a given region. Indeed, if we examine the distribution of various tree-types, we find that their boundaries coincide, approximately, with the normal axes of the various groups. The normal axis II (see Figs. 1 and 2) called by Multanovski the North Cape Axis, forms the westerly boundary of the larch and fir trees, and the extreme westerly positions of the isolated forests of this type coincide with the extreme westerly positions of this axis in certain years. The boundary of cedar, an even more distinctly Siberian product, is given by axis III, the Kanin Axis. On the other hand, European witch or yoke-elm does not grow east of axis I, middle Scandinavian. The "predsteppes" (transition-zone between the steppes and the forest) boundary coincides with the characteristic winter tracks of maxima moving from east to west over the central zone (so-called intrusion of a branch of the Siberian maximum).

It was found that some of the axes are characterized by great stability. The movement of anticyclone along a single axis often continues for a long time. This property might be utilized in the comparison of seasons among themselves according to the distribution of axes, as well as for comparison of each season with typical axes. In the latter instance we can determine the degree of deviation from the normal. The change in direction of a trajectory, or degree of deviation from normal, serves as a definite characteristic of a single season or period.

The passing of a maximum along an axis is bound up with a definite distribution of pressure over a large operating area, making the process complicated. However, it is this complexity which makes it possible to appreciate a series of very important situations, provided the map includes the entire operating area. (An operating area or natural region is defined as a region

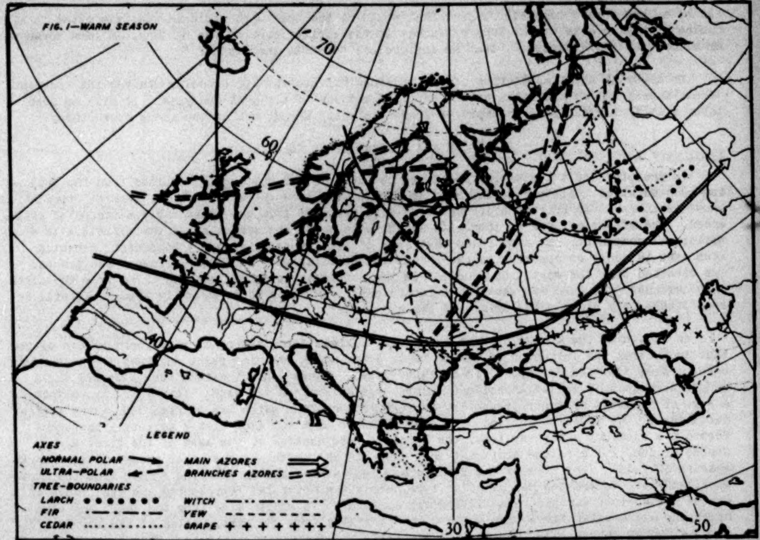

FIG. 1—WARM SEASON

70
60
40
30
50
LEGEND
AXES
NORMAL POLAR
ULTRA-POLAR
MAIN AZORES
BRANCHES AZORES
TREE-BOUNDARIES
LARCH ● ● ● ● ● ● ●
FIR
CEDAR
WITCH
YEW
GRAPE + + + + + + +

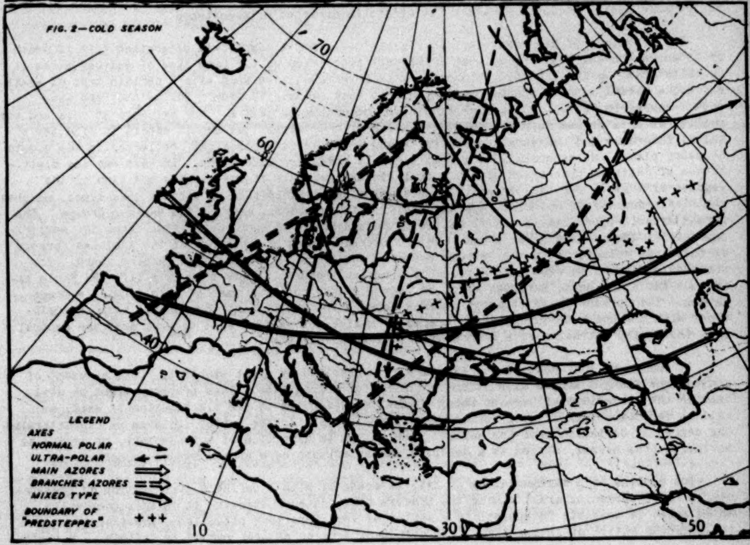

FIG. 2—COLD SEASON

70
60
40
10
30
50
LEGEND
AXES
NORMAL POLAR
ULTRA-POLAR
MAIN AZORES
BRANCHES AZORES
MIXED TYPE
BOUNDARY OF "PREDSTEPPES" + + +

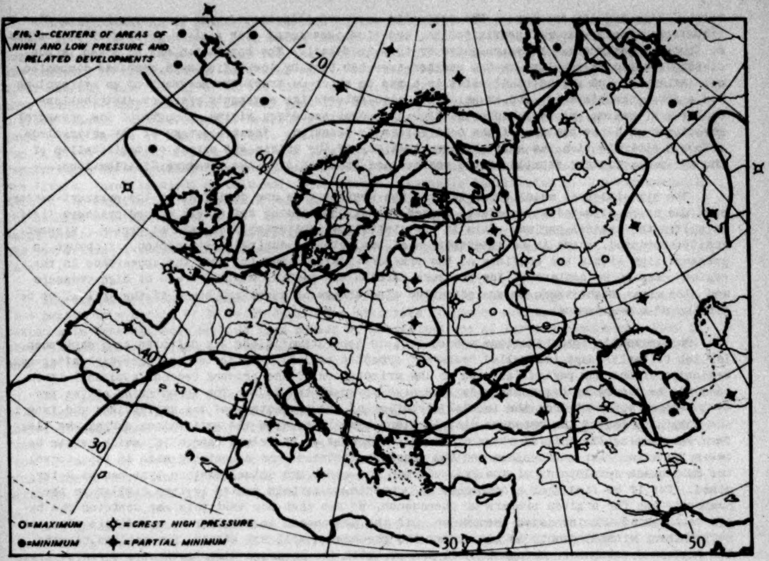

FIG. 3—CENTERS OF AREAS OF HIGH AND LOW PRESSURE AND RELATED DEVELOPMENTS

which includes the entire system of axes taking part in the establishment of the weather over that region.)

To gain an estimate of the distributions of pressure-areas during certain "developments" (the movement of a maximum along a definite axis) the method was used of entering on a map with the aid of special symbols the centers of areas of high and low pressure and related developments (crests of high pressure, secondary minima) accompanying the movement of the maximum (see Fig. 3). The maps obtained that way differ essentially from the mean pressure-maps, for example, in that they retain all the details of the life-history of the pressure-regions. We get, for example, an accumulation of cyclonic centers, and this shows that the conditions for the development of cyclonic activity in a given region were at hand; if in due course there were to appear in this region signs of partial minima and crests of high pressure, it would serve as an indication that conditions would become worse. The region of accumulation of this or other sign of pressure is called a field (cyclonic, anticyclonic, etc.). It was found that when the process is orientated in a definite manner as, for example, when a development (high) takes place along a certain axis, or when a certain weather-phenomenon occurs in a definite region and in other analogous cases, the centers are grouped into definitely distributed fields of high and low pressure. Only when this condition is observed can one figure on getting well-defined pressure-fields. In turn, when this selection is carefully observed, the change which appears in the pressure-state of one or several fields will serve as an indication of the change in the orientation of the axis and hence the termination of conditions favorable for the realization of a certain weather-phenomenon; and conversely a deviation from the normal trajectory implies a change in the pressure-field. The construction of a composite map is of significance then for any well-defined process. The relationship between the orientation of the process, in part between the movement of the maximum along a definite axis and state of pressure-field on the composite maps, is often utilized in practice. Thus, Multanovski's investigations have shown that the pressure-fields and axes are closely connected with each other, and that with the aid of the axes one can determine the distribution of pressure-fields and conversely a change in the orientation of the process can be determined from the distribution of pressure-fields.

The orientation of a process or phenomenon corresponding to a certain pressure-distribution associated with it is established in part by entering on a map the successive positions of centers of high and low pressure. The composite maps are illustrated with the corresponding distributions of temperature, precipitation, and wind associated with a given process or phenomenon, so that the weather can be represented by them in detail. The conclusion may be drawn, a conclusion checked by results, that a weather-type can best be identified by a combined composite map (kinematic and statistical) which is a map on which we trace the movement of an anticyclone (in a sense the air-mass) and on which are also entered the aggregate pressure-distributions (centers of maxima, minima, ridges of high pressure, secondary minima, troughs of low pressure) associated with the passage of the anticyclone in question. The trajectory of the anticyclone allows a determination, as a first approximation, of the origin and extent of modification of the air-mass; further details of the weather are obtained from the pressure-distributions.

The time-interval which characterizes the weather-type and during which the pressure-centers continue to be situated in separate, closed-in regions forming definitely marked pressure-fields is called the natural period. This is the statistical criterion of a natural period. Kinematically expressed, there is no intersection of trajectories during such a period. A change in pressure-sign within the confines of the pressure-fields, that is, when the appearance in the region occupied by centers of low-pressure (minima and partial minima) areas of high-pressure and vice versa might serve as an indication of a change of axes, and hence of the arrival or beginning of a new period.

Multanovski's investigations showed that an "operation" along any definite axis continues for ten to twelve days (so-called "natural" synoptic period). Hence two to three days after the beginning of the new period (as soon as the orientation of the process becomes apparent) it is possible to determine the weather for the next seven to ten days. The orientation of the process becomes apparent from the initial direction of the trajectory of the anticyclone and from the composite map of the pressure-distributions associated with the anticyclone during the time-interval marking its initial stage of travel. Because of the close connection which exists between the axis of an anticyclone and the pressure-distributions associated with it (see above) the subsequent development of the synoptic map and hence the actual weather-type can be determined. For if we find that a composite map covering a certain period is very similar to the composite map for a given process or phenomenon, we can then say that this map contains the basic features of the indicated phenomenon. If the phenomenon is peculiar to a definite place or region then, without doubt, in many cases the phenomenon will not attain, for various reasons, its fullest development, though it will occupy, with its pressure-distribution, a definite area.

Experience has also shown that a phenomenon or process materializes within a period not exceeding 30 to 35 days after the appearance of certain significant developments. In other words, the orientation of a process can in some cases be established earlier. In general, it can be concluded that indications of future pressure-distributions appear on preceding maps and that we can get an idea of the presence of a maximum number of such indications by the construction of composite maps.

It was found that following through the development of a large atmospheric disturbance we can select a number of phases which precede the occurrence of such a disturbance and also some of the stages which lead to the reestablishment of the disturbed equilibrium. This should be true also of extended processes. It was observed that in the occurrence of any typical phenomenon, preceded by a whole series of changes leading to the phenomenon, there is usually observed 30 to 35 days previously some change--a sort of "flaring up" of a new process, in our terminology "a threatening situation," or simply "a threat." Within this indicated time-interval one can distinguish approximately five more "moments." The pressure-distributions corresponding to these "moments" represent the initial steps in the phases of the development of a certain process which culminates in the investigated weather-phenomenon or leads to a "development" along an axis having a definite direction. Thus the time-interval $\Delta t \pm \delta t$ which precedes a certain process or phenomenon is subdivided into smaller intervals t_{-k}, t_{-k+1}, t_{-k+2}, ... during each of which the barometric condition is characterized by some definite, always realized, outstanding symptoms. The first moment t_{-k} is called a threat-symptom.

Having such phases one can enlarge the forecasts considerably since we know, for example, that a certain phase in the development of a glaze-process is connected with blizzard-conditions in a given region, while another phase indicates by its pressure-distribution, for example, conditions accompanying the Neva floods and storms over the Baltic.

Thanks to a systematic introduction of phases in forecasting practice, beginning with 1925, it became possible somewhat to widen the scope of forecasts for a period; for if it is evident from the phases that in the next period one can expect blizzard-conditions or a severe cold wave, then naturally there is no reason for the postponement of such a forewarning.

The determination of phases for various phenomena is made difficult to a large extent by reason of the fact that once a phenomenon characterizes a given season, that is, conditions during a certain season are favorable for the realization of this phenomenon, then the latter has the tendency to repeat itself more than once. For this reason one must not expect only situations whereby from the day of threat to the day of occurrence of the event itself one should have phases of only one given series, that is, the event to occur but two or three times during a given season. What ordinarily happens is that during the development of the process there appears a new threat of the same event, and hence there is noted a new series. Thus, during a season, a given event may repeat itself six to eight times. Naturally here too exists a definite regularity. Nevertheless, such combinations made the investigations much more difficult. In the future, investigations of this sort will become materially facilitated by the circumstance that in the realization of phases a part must be played by coupled centers of action and definite natural combinations of axes. At the present it is already clear that there cannot be a large number of phases, even if there is an interval of 30 to 35 days between the "threats" and the event itself, because the changes in the centers of action cannot proceed at a very fast rate.

The length of a phase ranges from six to fifteen days. On the average there are four to five phases to a period of 30 to 35 days. The principle of phases and threatening moments associated with them has been applied in a number of investigations of various phenomena. Some of these investigations will be discussed here. Of these the phenomenon of glaze was studied in some detail by E. S. Lyr.

As a phenomenon which often repeats itself during the winter, it should show a connection with regard to time as well. This connection was expressed in the formation of cold crests or nuclei of high pressure in the northeastern part of European Russia a month (± 2, 3 days) ahead. These crests or ridges appear either on the periphery (in front) of the anticyclone which arrived from the west, or directly from northern latitudes. Its appearance against a background of generally low pressure and replacement, almost always, on the following day, by a depression indicates an energetic activity of the Kara center of action, a sort of pulsation.

The pressure-centers on the day of appearance of the northeast nucleus, called briefly a "threatening day," when entered on one map, also appeared to be gathered in groups of one sign (pressure). On the threatening day which corresponds to the westerly type of glaze (two types of glaze are recognized depending on the origin of air-masses involved) a large part of European Russia appears under a sign of high pressure. On the map corresponding to the easterly type, the maximum occupies the east, the southwestern portion of U.S.S.R., and Scandinavia. At the very first sight the similarity of the main features between the composite map of the threatening day and the day of occurrence of glaze of the corresponding type stands out clearly. This was observed in all the examined cases of glaze. It should be noted that not only the initial and final stages of glaze-phases, namely, the threatening day and day of actual occurrence, but also some of the intervening periods have the same pressure-sign in most areas.

Next comes the question of determination of the region where the phenomenon is expected to occur. One should expect that the synoptic situation in the region where glaze is to occur would be subject to a definite set of changes. These can be recognized. The most pronounced indication appears, however, on the thirteenth to fourteenth day after the appearance of the threatening nucleus. This period occurs in the third phase. On this day the region where glaze is to occur is occupied by the cold crest (or even maximum) whereby the isobar forming this crest and the isotherm which encloses the region of low temperatures embrace, sometimes very definitely, the region where glaze is threatened. The day on which is indicated the region where glaze is to occur in the future is called the "regional" day.

It is said that the isobar and isotherm of the regional day mark "sometimes very accurately" the boundaries of the district where glaze is to occur because the greater or lesser degree of occupation of this region depends obviously on the intensity of the phenomenon, which has not as yet been determined. Thus there was one instance when not a single case of glaze was reported in the district indicated (forecast for period March 14-19, 1924, when glaze occurred east of the district indicated). However, the relative distribution of pressure-areas for that period is such that glaze is to be expected in the very district indicated, as it happened in the synoptically analogous case of December 5, 1912. Thus in the present case the orientation of the process as well as the subsequent pressure-distribution were correctly indicated, but the intensity of the phenomenon did not attain that degree of development which is essential for the falling out of super-cooled droplets.

Other investigations--The characteristic indications of storms on the Caspian were investigated by another follower of the Multanovski School. The investigator finds that the occurrence of this phenomenon is always accompanied by the arrival of a cold wave from the Kara Sea--Taimir Region. Irrespective of type of storm (anticyclones which are involved in its development) it is the intrusion of a cold wave from the above-mentioned region which makes the storm possible.

In one of the earlier works of Multanovski it is shown how the occurrence of northeast storms on the Black Sea can be estimated on the basis of a composite map of the phenomenon.

In another investigation which dealt with synoptic conditions accompanying ice-jams (zajores) the author found that during the years characterized by a strong development of this phenomenon there was noted an intensification of the disturbance along the axis lying close to the Kanin normal.

III--Forecasting for seasons

One of the fundamental principles of forecasting for a period is that, knowing the direction of the segments of trajectories of the significant pressure points during the period, one can, in principle, give the weather-characteristics of this period.

A season consists of natural periods which are characterized by definite operations. In order to divide the year or season into periods it is necessary to enter on a map, beginning with a certain date, the centers of pressure-formations up to the time the pressure-fields retain their signs unchanged. From the moment, when for example an anticyclonic symbol appears on the cyclonic field, or the reverse, the period shall be regarded as finished, and a new one is at the same time begun. Having established the end of a period and obtained a composite map thereof, the latter is completed in the same manner by entering the preceding days of the period and thus its initial day is obtained. In practice such a division offers a convenience in that, given a pair of initial days, one can indicate the entire distribution of pressure-areas which will hold till the end of the period.

The season itself is determined by the predominance of a certain axis which serves as its dynamic characteristic and distinguishes it from other seasons. One can say that the beginning of each season is determined on the basis of some completely developed characteristic seasonal process which later may repeat itself several times during the period in question. A change of seasons takes place during the synoptic period. A curious property of the season appears to be a constancy of certain areas of maxima and minima for the entire interval corresponding to it on all the composite maps. This allows a determination of the weather-types.

It was noted that the composite maps for a period represent a rather simple distribution of pressure-formation and in this respect they closely resemble maps of phases and separate weather-phenomena. The seasonal maps appear to be much more complicated since on them are reflected the "developments" along the entire combination of seasonal axes, the occurring weather-phenomena characterizing the season as well as the first signs of new operations characteristic of the coming season. On account of this the pressure-fields occupy a much smaller area on seasonal maps and are distributed closer to each other than on the maps of the periods. If the centers of maxima and minima were to be carried over directly from the composite maps for the periods onto the seasonal maps, a series of this or another sign would no doubt also have been obtained but the dividing line or zone, so-called line of demarcation, would also have been filled with signs of that or the other kind, making the analysis of such a zone considerably more difficult.

In preparation of forecasts for seasons the procedure similar to that used in periods is followed. Given composite maps for a set of adjacent seasons the state of pressure-fields of the season just ended is compared with the one which preceded it. First are noted regions (geographical) where the pressure has assumed the reverse sign, an indication of the beginning of one season and the ending of another; then the regions where the pressure-sign has not suffered any changes are located and finally the regions where the fields have experienced smaller changes, for example, where maxima become supplemented with ridges of high pressure and minima with partial minima, or the reverse, are determined.

Denoting all the customarily encountered changes in the state of pressure with special symbols and applying the latter to the case under consideration a geographical distribution of the changes in the pressure-field as well as the character of these changes is obtained. Such a comparison enables one to establish in which direction the change in pressure-conditions takes place, and thus, by extrapolating, the composite map of the coming season can be constructed.

Multanovski also states that the extrapolation is made markedly easier and endowed with a larger probability (especially for the districts where a change in sign takes place) if both halves of the season just ended are worked up in an analogous manner. [These halves are determined on the composite map through the circumstance that there occurs at about that time a sort of attempted shift of the pressure-fields, an inception of a new process.] This would lead one to presume that there are two main periods to a season.

Having entered symbols of both series on one map there are obtained--depending on the amount of available detail--from 40 to 80 districts formed by western half of Siberia, Europe, and the ocean bordering it, which are used in the extrapolation. When the latter is carried out and expressed with the usual symbols, the required composite map for seasonal forecasting is obtained. The map obtained is then confronted with a collection of composite maps on which are given the axes. By examining the distribution of pressure-areas on the seasonal map one can select from the atlas of composite maps the expected operating axis for the typical axis. By making use of temperature, wind, and other characteristics of typical axes, one can obtain a whole set of details which have practical interest. Analogously, from the similarity of the pressure-distribution on the composite map during specific and seasonal situations one can determine the weather-types, characteristic of the season, and districts where they occur.

As a result of the comparison the extrapolated map is usually found to contain two or three separate types of weather. In order to bring about the division of the composite map into natural periods it is necessary to establish whether all the pressure-regions which appear on the map can exist simultaneously, and if not, to select those situations which are common to one another and are coexistent.

Although it is known that there usually exist two or three types it is not possible yet, unfortunately, to establish the order of sequence of the types. Therefore, in making the forecast for a season it can only be indicated that the season will be characterized by the presence of such and such weather-types without indicating the exact time of their realization. This is obtained later when forecasts for natural periods are issued.

Classification of methods--The methods used in preparation of forecasts can be classified as follows:

(1) Method of analogous cases--(Two or more statistical composite maps can be regarded as analogous if when properly constructed they should prove to be kinematically analogous.) This method is used but seldom.

(2) Extrapolation of dominating processes from one composite map to another which gives the trajectories and positions of regions of maxima and minima. This is made on the basis that the process under investigation is often conditioned by a set of long-lasting, almost constantly directed, currents in the atmosphere.

(3) The application of phases--For, as was found, a synoptic period appears very often as a phase of one or several processes which will occur in the near future. The phase-method is considered one of the best and most accurate. For, knowing the structure of the composite map and consequently the nature of the processes corresponding to the following phases, one can often indicate, quite accurately, the general character of barometric processes for the following period and sometimes also for the period following it.

(4) A known set of empirically obtained relationships between processes of two consecutive seasons.

Composite maps--Because of their significance the various types of composite maps are briefly defined here.

The statistical composite map of a phenomenon (map of significant pressure-points) constructed for the period during which it occurs, allows a determination of the schematic structure of the pressure-fields and also of the characteristics and indications which are necessary for the realization of the phenomenon in question.

The statistical composite map of a phenomenon which is constructed for some moment which precedes its realization allows a determination of the schematic structure of the pressure-field and also of the characteristics which indicate that the coming phenomenon will occur within a certain time-interval $\Delta t \pm \delta t$ (where $\pm \delta t$ is the possible fluctuation of the interval Δt).

The kinematic composite map of phenomena allows a determination of the kinematics and dynamics of a barometric process on which the realization of the studied phenomenon is contingent. (Map of trajectories of maxima and minima.)

The kinematic composite map for some period which precedes the occurrence of the phenomenon allows the determination of the kinematics and dynamics of the barometric process on which depends the realization of the coming phenomenon within the time-interval $\Delta t \pm \delta t$. (Composite maps of trajectories of maxima for a certain period.)

A similar classification holds for composite maps for a synoptic process. The composite maps of processes allow the determination of (1) regions of a stationary barometric field, (2) pressure-regions related and unrelated to a given process, which offers the opportunity to select the so-called natural or normal region for the given process--by normal is meant a process which constantly repeats itself in a certain region, (3) dependent and independent neighboring processes, (4) necessary statistical, kinematic, and dynamic conditions of the process for the period of its realization as well as for any period preceding it, (5) phases of the process. Finally, there are composite maps of synoptic processes for longer time-intervals, periods, and seasons.

Sample forecasts, past and present--To show the development of the long-range forecasts from the time they were first issued to 1930, E. Tichomirov includes in his paper several examples, some of which are given below.

The first attempt at forecasting was made in 1915 for the Kara Sea Region in connection with the work of freeing an expedition held by the ice. It proved highly successful. From 1919 Multanovski began to issue forecasts, first under his own name and then, beginning with the summer of 1922, by the authority of the Central Geophysical Observatory. At first they were not issued regularly, but to meet individual demands. Here are some examples.

June 1921 was marked by poor weather. It rained almost every day. On June 25 there came an inquiry regarding the weather for the next two to three weeks. The inquiry came from an agricultural organization concerned about the hay-cutting season. The forecast given was as follows: "The current period of unstable weather will continue approximately till July 2. Some improvement will probably occur towards the end of the period. Fair (stable) weather is to be expected in the region in question in the following period and will be most pronounced around July 10." The forecast was verified.

On September 15, 1921, the Department of Foodstuffs made an inquiry about the fall weather. The specific problem was: What period would be favorable for the transportation of potatoes? The forecast issued was as follows: "There is to be expected, during this fall, the passage of cold waves predominantly over western half of European part of U.S.S.R. and the central districts. Such a situation appears to be quite abnormal and apparently it will be strongly developed. As a first approximation a weak cold wave is to be expected during September 23-25 and a more intensive one around October 5. On the basis of the foregoing the Observatory deems it necessary to say that the transportation of potatoes should be hurried in order that it be finished by the beginning of October."

In 1923 the Bureau forecasted the overflow of rivers in northwestern Russia two months ahead. Again this proved to be accurate. Measures were taken early and no break in transportation occurred.

The spring of 1924 was described in the forecasts as "arriving slowly but fully developed." It was also stated that the possibility of a drought is not precluded in the region of Lower Kama-Bela River Watershed. This was verified.

Tichomirov quotes a number of other examples, one of which is especially interesting. In April 1931 it was feared by many that the coming summer would be very dry and therefore accompanied with crop-failure as were the predecessors of the series of "Black Years," 1881, 1891, 1901, 1911, 1921. In order to obtain any indications of this Multanovski examined a whole series of existing observations and established that there exists a connection between the basic winter and spring processes which is expressed by the circumstance that in 85 per cent of the cases a normal spring process is followed by a normal winter process. It also appeared that all the summers of the above-named series (Black series) were preceded by an abnormal development of the spring process and since the process during the winter 1930-31 was close to normal Multanovski could state that there existed only a mere possibility of local drought and rejected the possibility of the recurrence of the catastrophe of 1921, etc. Indeed, nothing resembling the summers of that series was observed in 1931.

A systematic verification of the forecasts was made in 1931 by G. Wangenheim who examined 178 long-range forecasts issued during 1928-30. It appeared that the forecasts covering natural periods gave an 89 per cent verification for precipitation, 75 per cent for temperature, and 67 per cent for the combination of the two. He also found that "forced" forecasts, that is, not for natural periods, gave a much lower verification.

A typical monthly forecast includes first a long discussion of probable movements of areas of high and low pressure over Europe and adjoining territories for the period in question; then the general weather-characteristics are indicated. All dates are pointed out precisely. The margin of tolerance is ± 2 days.

Here, for example, is part of the forecast for August 1935:

"Region (1), northern area, period August 2-8--Unsettled weather; cloudiness decreasing toward end of period, then clear...passing rains...winds fresh to moderate in the beginning of period, then decreasing...temperature 16° to 7°, rising towards end. (Temperatures are given for morning observations.)

"Period, August 16-22: First half--Varying cloudiness, without rain. Great increase in cloudiness in the second half of period. Rains light to moderate. Temperature range 14° to 7°." Then come the forecasts for the other districts. The country, we had occasion to remark, is divided into 40 to 80 areas depending on the weather-types which are operating.

Concluding remarks

No attempt was made in this paper to give a critical analysis of the Russian School of long-range forecasting. An evaluation of the principles and methods of that School will be made, it is hoped, at a later date. The methods are in a continuous stage of development. With the introduction of air-mass analysis in the Soviet Union and application of new principles to long-range studies, improved long-range forecasts are to be expected. At present the success of the long-range forecasts appears to be considerable.

The relatively great success of the Russian meteorologists is not surprising. Russia represents a vast area of flat land at no point rising more than 1000 feet above sea-level. The soil over the greatest extent of the country is comparatively uniform; it is little tampered with by man. It represents the nearest to an ideal laboratory provided by Nature in which can be studied the weather on a large scale under simplified conditions. It was probably this that moved H. von Ficker to say that Russian meteorology stands in a better position to solve the problem of long-range weather-forecasting than anyone else.

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The publications dealing with the theory and methods of the long-range forecasts discussed above are, with one exception, in Russian. Most of them are accompanied by brief résumés either in English, French, or German. The exception is a paper by E. S. Lyr listed as [9] in the bibliography given below and is written in English. It contains a general synoptic study (preliminary) of droughts. The three papers in which an exposition of the methods is attempted or made in part are listed, respectively, as [10], [11], [12]. No paper contains a complete exposition of the subject. The order of the papers listed below is historical.

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METEOROLOGICAL FEATURES INDICATED BY AIR-CONDUCTIVITY MEASUREMENTS MADE ON FLIGHT OF EXPLORER II

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The electrical state of the free atmosphere up to nearly nine kilometers had been explored by a number of European physicists prior to the flight of Explorer II. They usually employed manned balloons of the open-basket type. Those observations led to the inference that the electrical potential of the air increases with altitude but at a diminishing rate, so that the potential gradient decreases with altitude, whereas the air-conductivity increases and at a rate such that the product of conductivity and potential gradient, or the air-earth current, at a given instant is roughly the same at all levels. There are, of course, departures from that trend, many of which are associated with meteorological features.

The phenomenon of lightning gives evidence of the very great departures around and within clouds of the cumulo-nimbus type. Measurements made in balloons indicate that every type of cloud presents a marked departure from the electrical state of the cloudless atmosphere. Even temperature-inversions seem to have associated with them electrical charges which produce conspicuous deviations from the trend of the potential gradient. The boundaries of haze-layers are also thought to correspond with levels where potential-gradient changes are observed.

On the day of the flight of Explorer II, November 11, 1935, clear weather prevailed over the entire region traversed by the balloon. Hence the effects of clouds upon the registrations of electrical conductivity did not come into account. No well-marked haze-boundaries were noted, and, although a few temperature-inversions were indicated by the air-temperature data, the air-conductivity showed no such definite associated effects as have been reported by Linke, Gerdien, Wigand, and others [see 1 of "References" at end of paper].

What shall here be designated "meteorological indications" were derived from the observations by methods of interpretation which require some explanation. A more complete report, including a description of the apparatus and method of measurement, as well as results and interpretations, will be published in a future issue of the Journal of Terrestrial Magnetism and Atmospheric Electricity.

Air-conductivity depends upon the abundance of ions in the air and upon their mobility. Thus $\lambda = e(n_1k_1 + n_2k_2)$ where λ represents the total conductivity, e the electronic charge, n_1 and n_2 the number per cubic centimeter of positive and negative ions, and k_1 and k_2 their respective mobilities. The two terms on the right-hand side are measured separately and are designated positive conductivity (λ_1) and negative conductivity (λ_2).

In order that the air-to-earth electric current be continuous the number of positive ions must, on the average, be nearly equal to the number of negative ions at a given level, except near the Earth's surface, and hence the ratio of polar conductivities (λ_2/λ_1) should be proportional to the ratio of mobilities (k_2/k_1). From laboratory measurements it appears that this ratio is dependent upon the humidity of air, that it is independent of temperature, and that it depends on pressure at low pressures only, beginning to increase at 200 mm of mercury and increasing quite rapidly at pressures below 100 mm. If this pressure-variation is the correct interpretation of measurements in the laboratory, then the negative conductivity should be about eight or ten times the positive values at the highest altitude, instead of about 1.3 which is the laboratory-value at atmospheric pressure, and which is consistent with the present data at all levels as can be seen from an examination of Figure 1. (Although this is the interpretation generally accepted by the authors of most treatises on the conduction of electricity in gases, yet on closer examination one finds grounds for doubting it.)

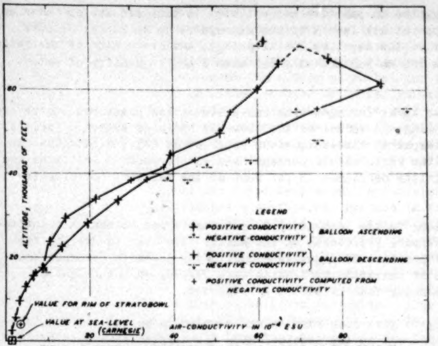

FIG. 1—ELECTRICAL CONDUCTIVITY OF AIR, FLIGHT OF *EXPLORER II*, NOVEMBER 11, 1935

In Figure 1 altitude is plotted as ordinate and polar conductivity (λ_1 or λ_2) as abscissa. Crosses mark mean values of positive conductivity, while horizontal dashes mark those of negative conductivity. An arrow-head, affixed to these marks, points upward for values obtained on the ascent and downward for those registered on the descent. However, some crosses are without arrow-heads. The values corresponding to these were derived by dividing the observed negative conductivity-values by 1.3. The alignment of these with the points for directly observed values of positive conductivity is such that one may conclude that the ratio of mobilities remained nearly constant at all levels except the highest. At that level the ratio is less than unity but the negative conductivity-values are too small because, at the low pressure there, conditions for an ohmic current in the Gerdien condenser were no longer fulfilled for the negative conductivity.

If the results of investigations in the laboratory, as interpreted, may be relied upon, then

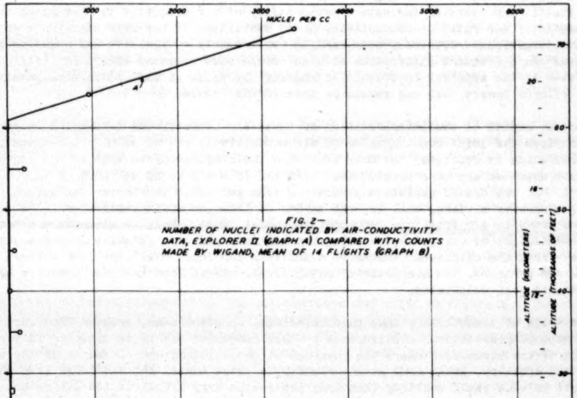

FIG. 2—
NUMBER OF NUCLEI INDICATED BY AIR-CONDUCTIVITY DATA, EXPLORER II (GRAPH A) COMPARED WITH COUNTS MADE BY WIGAND, MEAN OF 14 FLIGHTS (GRAPH B)

the observation that the ratio of negative to positive conductivity is constant may be taken as evidence of the presence of water-vapor at all levels in the atmosphere up to 22 km, because Lattey [2] reported that the increase of the negative mobility (k_2), and hence also of the ratio k_2/k_1, with decreasing pressure below 200 mm was not so great when a small quantity of water-vapor was present.

But even if one questions whether λ_2/λ_1 for aged ions increases at low pressures, there are other reasons for tentatively considering the values of the observed ratio as evidence for the existence of water-vapor in the stratosphere. Investigations by Erickson [3] indicate that in very dry air at atmospheric pressure the ratio should perhaps be close to unity. Griffiths and Awbery [4] find that the negative mobility decreases 18 per cent as the relative humidity increases from 0 to 100 per cent.

While the results of investigations in the laboratory do not enable one to make a quantitative estimate of the amount of water-vapor, yet, taken on the whole, they seem to justify the conclusion that the observed ratio of positive to negative conductivity presents evidence that water-vapor was present at all levels of the atmosphere which were reached on the flight of *Explorer II*, and likely in greater quantity than is generally supposed.

That water in sufficient quantity to give such results was carried up by the balloon is doubted, because the mobility-ratio observed on the descent, when the Gerdien condenser of the conductivity-apparatus was continually rushing into fresh air, was the same as that for the ascent. Although there is evidence for concluding that the values of conductivity measured on the ascent were affected by nuclei given off by the balloon, whereas those measured on the descent were not, yet the number of nuclei required to appreciably affect the air-conductivity is exceedingly small compared with the number of water-molecules which would seem necessary.

The justification for stating this tentative conclusion is not the conclusion itself but rather that it may serve to indicate a potentiality of air-conductivity measurements or of direct measurements of the ratio of conductivity or of mobilities in the high atmosphere as a tool in other investigations. Obviously simultaneous measurements of positive and negative conductivity, or at least more frequent alternation of sign, would have enhanced the reliability of the ratio, and in view of the apparent importance of knowing the value of that ratio with greater precision, further efforts toward that end should be made in the future.

Another aspect of the interpretation of these air-conductivity data which bears on meteorology involves the joint consideration of air-conductivity and of cosmic-ray intensity. The cosmic radiation is doubtless the only important ionizing agency in most of the region of the atmosphere which we are here considering, that is, from 1.5 to 22 km (5000 to 72,000 feet) above sea-level. If the cosmic radiation produces q ions per cubic centimeter per second, then the population density of ions, that is, the number of ions per cubic centimeter (n) under equilibrium-conditions in air free from condensation-nuclei, dust, etc., is given by $n = \sqrt{q/\alpha}$, where α is the coefficient of recombination between small ions and is a function of temperature and pressure. From the calculated values of n and from the ionic mobility, also a function of temperature and pressure, the conductivity which should result from the ions produced by the cosmic radiation has been calculated.

The value of conductivity thus calculated was, in every case, greater than that observed at the corresponding altitude. A difference of this character was to be expected in the lower five or six km of the atmosphere where the presence of condensation-nuclei decreases the conductivity because the ordinary, small ions attach readily to these nuclei and the large ions which are thus formed are of such small mobility that they contribute very little to the air-conductivity. However, one can scarcely think that the difference between the calculated and observed values of conductivity at altitudes above six km (20,000 feet) is attributable to the presence of nuclei. The required number and distribution would be very difficult to account for and would present a marked contradiction to the direct nuclei-measurements made by Wigand [5].

Furthermore, the calculations may be questioned in one respect. Thomson's theory, which was followed in the preliminary calculations, says that the recombination-coefficient (α) for small ions varies as the first power of the pressure, but there is as yet inadequate experimental verification of this. While some measurements in the laboratory seem to check this, others show marked disagreement. If, however, the one-half instead of the first power of pressure is used, then the calculated and observed values for conductivity agree closely over the 12-km range of altitude from 6 to 18 km. In the final calculations, namely, those discussed in the following paragraphs, it was therefore assumed that the small-ion recombination-coefficient varies approximately as the square root of the pressure.

Below six km (20,000 feet) and above 18 km (60,000 feet) the revised calculation yields values which are greater than those observed. If these differences are attributable to the presence of nuclei, then their distribution in the atmosphere up to 22 km at the time and place of this flight may be described with the aid of Figure 2. In that Figure ordinates represent altitude and abscissa represent the number of nuclei per cubic centimeter. The means of values observed by Wigand with an Aitken counter on 14 balloon-flights are also shown here by the broken curve. Although the individual values which go to make up his means fluctuate over a considerable range, especially at the lower levels, yet apparently on the average the number of nuclei over central Europe, where his observations were made, decreases with altitude in a fairly regular manner, becoming negligibly small at about six-km altitude.

The number of nuclei per cubic centimeter as calculated from the conductivity-data is of somewhat doubtful quantitative significance, because it is not definitely known how some factors (namely, the combination-coefficients of small ions with large ions and with neutral nuclei) involved in such a calculation vary with temperature and pressure. However, it is thought that the values shown graphically in Figure 2, especially those for the lower levels, are a sufficient approximation for the present purpose, which is chiefly to indicate what sort of information of meteorological interest may be derived from a joint consideration of measurements of air-conductivity and of cosmic-radiation intensity. [The cosmic-radiation-intensity data published by E. Regener and G. Pfotzer (Physik. Zs., v. 35, pp. 779-784, 1935) were selected as the most suitable data available for these calculations; they were obtained at nearly the same magnetic latitude as that of the region covered by the Explorer II.]

No estimate of the distribution of nuclei at levels below 1.5 km (5000 feet) can be made from the air-conductivity data except by extrapolation, which indicates that the nuclei-content in that region was less than the average observed by Wigand. This seems reasonable because in the sparsely settled area over which the conductivity-measurements were made there are no large cities and relatively few towns such as doubtless contributed large numbers of nuclei to the atmosphere in the regions where Wigand's observations were made. The number indicated at levels between 1.5 and 6 km is greater than that reported by Wigand. This body of air appears to be of Polar Pacific origin but the indicated number of nuclei is somewhat greater than has been observed at sea on the Carnegie. It therefore seems likely that additional nuclei have been carried to these altitudes while this air was traversing land where the number of nuclei at the surface is generally much greater than at sea.

From analyses kindly supplied by the United States Weather Bureau, it appears that Polar Pacific (P_p) air overrunning polar-continental air extended from about two-km to more than three-km elevation and that above this a layer of active transitional Polar Pacific (N_{pp}) air extended to a height of over four km. The excess of nuclei, relative to the trend indicated by Wigand's data, appears to be associated chiefly with the Polar-Pacific air-masses. That there could have been sufficient mixing to carry nuclei up from the Earth while these air-masses crossed the 1000 miles of high plateaus and mountain-ranges seems not unlikely. In a study of dust-storms which occurred over the Great Plains in recent years, G. R. Parkinson [6] remarks that in many cases the dust was confined to transitional Polar-Pacific air. This may be taken to indicate that conditions in N_{pp} air are such as to keep nuclei in suspension for relatively long periods of time.

The greatest surprise presented by the calculations exhibited in Figure 2 is the indication of considerable quantities of nuclei at altitudes above 18 km (60,000 feet), the number increasing from that level to the highest altitude reached (22 km). The balloon apparently entered a different air-mass at about the same level as that of the lower boundary of this bank of nuclei. The air-movement here was brisk from the west-southwest, which suggests that this air may have been of tropical origin. This surmise is entertained because several observers have reported that nuclei are relatively abundant in surface-air of tropical origin.

One might speculate as to other possible sources of these nuclei, such as volcanic eruptions, the disintegration of meteors, or the more general capture of matter from cosmic space. Since the range of speculation here is not yet limited by much quantitative information, one may also be free to surmise that ozone, which becomes especially abundant in about this same region of the atmosphere, acts as an agent in the formation of nuclei. But until such speculation can be guided by a greater variety and abundance of quantitative information it is likely to be of little value.

It is thought that the investigation here described shows that measurements in the high atmosphere of air-conductivity and of cosmic-radiation intensity can be made with such accuracy that from them one may derive certain quantitative conclusions about some features, particularly in the stratosphere, which so far have been beyond the reach of other methods.

However, in order that the quantitative interpretation of such data may be regarded with greater confidence, it is desirable that further investigation in the laboratory be made of the following: (a) The variation of the mobility of aged ions with pressure and with humidity, especially the mobility of negative ions at low pressures; (b) the pressure-variation of the coefficient of recombination between small ions in low concentrations; and (c) the variation with pressure of the combination-coefficient for small ions with large ions and with neutral nuclei. It is hoped that the appearance of another need for such information in geophysics, if not in pure physics, will call forth the required investigations in the laboratory. [Items (a) and (b), especially the latter, are needed for a more satisfactory evaluation of some phases of ionosphere-theory.]

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AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

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REPORTS ON MAGNETIC AND ELECTRIC WORK OF ORGANIZATIONS IN NORTH AMERICA DURING 1935-36

MAGNETIC WORK OF THE DOMINION OBSERVATORY DURING 1935

R. Meldrum Stewart

During the year, magnetic work was carried on primarily for the purpose of securing secular-change data. Of the 33 stations occupied, at each of which the three magnetic elements (declination, inclination, and horizontal force) were determined, 27 are repeat and six are new. Five of these new stations are in the vicinity of stations previously occupied and were established in accordance with the practice of choosing a new site in case a station appeared likely to prove unsuitable for future occupation. The work was confined to two sections of the country, 18 stations being between latitudes 51° 09' north and 56° 24' north and longitudes 94° 36' west and 120° 53' west, and the remaining 15 between latitudes 45° 23' north and 51° 26' north and longitudes 57° 09' west and 76° 36' west. In addition to the regular field-work instrumental comparisons were made at Ottawa in the spring and autumn.

Dominion Observatory, Department of the Interior,
Ottawa, Canada

MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1935 TO MARCH 1936

R. S. Patton

Magnetic surveys--Due to what appears to be a marked change taking place in the rate of change of declination, additional repeat-observations were made in the eastern and middle western parts of the United States. In all, during the period, 60 stations were occupied in 19 states. This work completes the data for the 1935 isogonic chart. Other work was done incidental thereto, such as the replacement of old stations for the benefit of surveyors, declination-observations at triangulation-stations, and observations at airport compass-testing tables.

In Alaska and the Philippines, declination-observations were made at triangulation-stations. A survey was made of the local attraction of a harbor in the Aleutian Islands. An investigation was made of the effect of the local attraction in the vicinity of Wilmington, Delaware, on the compasses of vessels navigating the Delaware River. Some observations were made under State auspices with instruments loaned by the Bureau.

Magnetic observatories--The five magnetic observatories have been in continuous operation during the year. At Cheltenham the sine-galvanometer of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (referred to hereafter as DTM, the United States Coast and Geodetic Survey being indicated by CGS) has been used to determine horizontal intensity. The magnets of the horizontal-intensity variometers have been readjusted accurately to the magnetic prime-vertical. The cosmic-ray meter operated under the auspices of a committee of the Carnegie Institution of Washington has been kept in operation--routine by CGS and correction of difficulties by DTM. Four vertical-intensity variometers have been compared over a period of six weeks and two over a much longer period. A perminvar vertical-intensity variometer developed in the DTM by A. G. McNish has been kept in operation.

At Tucson, in addition to magnetic observations, atmospheric-electric and earth-current observations have continued through the same cooperation with DTM and the American Telephone and Telegraph Company as heretofore.

Development of instruments and methods--A joint program on development of electrical instruments was carried on with DTM. Some improvements in instruments and methods have been carried out as described in another paper by H. E. McComb (see his paper in these *Transactions*). The aim of this particular work is (1) to prevent errors creeping into instrumental performance with the passage of time, (2) to get results which will meet the needs of investigators and which will aid in maintaining proper standards, and (3) to obtain consistent performance as an aid to reducing amount of work in the office required to prepare data for publication.

Publications--Observatory-results for Sitka and Tucson during 1927-28 and for Cheltenham during 1929-30 are ready for distribution. All others except San Juan for 1929-30 are ready for reproduction and a start has been made on the series of 1931-32. Good progress was made on Polar-Year results. The Polar-Year records for both College-Fairbanks and Sitka in Alaska have been sent to the Polar-Year Commission.

"Magnetic declination in the United States for 1935" has been issued. An edition of isogonic charts has been prepared in form specially suited to aviators.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RECENT PROGRESS IN THE LABORATORY-INVESTIGATIONS OF THE AURORA AND LIGHT OF THE NIGHT SKY

Joseph Kaplan

One of the most interesting aspects of both auroral and night-sky spectra is the part played by oxygen in the production of those spectra. I have often pointed out that the absence of nitric-oxide bands in these two spectra is a significant feature. It is with the rôle of oxygen in upper-atmosphere spectra that most of my work during the past year has dealt.

The experimental method in these experiments was very simple. It was necessary first to prepare a discharge-tube containing pure nitrogen and showing a strong afterglow, the spectrum of which corresponded almost perfectly with that part of the auroral spectrum that is due to nitrogen. Certain improvements have been introduced in the preliminary treatment of these tubes, which lead to stronger afterglows than were previously obtained. These will be described elsewhere. The oxygen is generated in the tube itself by heating $KMnO_4$. In these preliminary experiments no method was available for measuring the oxygen-concentration or the total pressure in the tube. This part of the experiment will be left for the future. It was felt that the discovery of the qualitative aspects of the interaction between oxygen and nitrogen was by far the most important problem. The initial pressure of nitrogen in the tube was about 10 mm. The tube cleaned up steadily, so that after several months of running the pressure had diminished to about 0.01 mm, and in time it would have gone down to a vacuum so low that no discharge could have been produced in the tube. This clean-up of N_2 has been frequently observed in these "auroral" tubes.

The results are most readily indicated by describing the behavior of the tube as the oxygen which has been introduced into an "auroral" tube is cleaned up slowly. The time required for this clean-up varies with the pressure, and of course with the amount of oxygen that has been introduced. If sufficient oxygen is introduced, it is possible to completely quench the auroral afterglow and to replace it with a blue-green glow which possesses a continuous spectrum. As the tube is run, the oxygen slowly cleans up, and first this blue-green glow disappears. There is then an intermediate stage which shows no visible afterglow. This stage of the glow usually lasts about an hour after the oxygen has been introduced. Further clean-up is accompanied by the appearance of an afterglow, the spectrum of which is composed almost entirely of members of the first-positive system of nitrogen. Particularly strong are those members of the first-positive system which are observed in night-sky spectra, namely, those which originate on $v' = 15, 16, 17, 18$, etc. This is the most remarkable stage of the phenomenon because there is virtually no trace of the β bands of NO. At a similar stage of the Lewis-Rayleigh afterglow (the first nitrogen-afterglow), the first-positive bands are completely quenched and replaced by the NO β bands. This profound difference in the behavior of oxygen in the Lewis-Rayleigh and the auroral afterglows shows in a most striking way that the active nitrogen in the upper atmosphere differs in behavior from the classical active nitrogen of Lewis and Rayleigh. The agreement between the laboratory-observation of the absence in spectra of the upper atmosphere is a striking corroboration of the authenticity of our laboratory-model of the upper atmosphere.

It should be remarked here that the failure of the β bands to appear in these experiments indicates that there is probably very little formation of nitric oxide in the afterglow. This point is going to be carefully studied in the future. What rôle does oxygen play? The strength of the green auroral line in both night-sky and auroral spectra indicates that much of it remains in the atomic form. Tentative identification of certain night-sky radiations as bands of the Schumann-Runge system and of the atmospheric system of O_2 shows that much of the oxygen stays in the molecular form. These tentative identifications agree with our laboratory-observations on the action of oxygen on the nitrogen-afterglow.

After a few hours further running of the tube, the oxygen clean-up results in the disappearance of this second stage of the afterglow. It may be pointed out here that the time required for the building up and the disappearance of this stage varies with the total pressure. The maximum intensity of the afterglow also depends on the pressure. At certain pressures the afterglow in this stage is a very brilliant orange-red glow. As the total pressure diminishes the duration of this stage of the phenomenon diminishes, and finally completely disappears.

Further clean-up of oxygen results in the appearance of a bluish-white glow, at first very weak and then building up to a brilliant flash-glow which has as its spectrum the nitrogen-part of the auroral spectrum.

It is felt that preliminary reports on two other afterglow-phenomena may be of some value, and I therefore present them here. It was noticed on several afterglow-plates that the relative intensities of the two second-positive bands λ4356 and λ4344 were different than in electrical discharges. The band λ4356 originates on the (v' = 4) vibrational level of the $C^3\pi$ electronic state of N_2. The band λ4344, on the other hand, originates on v' = 0. In the afterglow the ratio of I_{4356}/I_{4344} is much larger than in the discharge. This indicates that the excitation-processes which are responsible for the afterglow are more capable of exciting the (v' = 4) level than are those in the discharge. This interesting difference in the two excitation-processes may prove to be the best means of determining whether the auroral and night-sky radiations are produced by electrical discharges or by an afterglow or phosphorescence.

This first phenomenon is of interest when considered in connection with the second one that we propose to present briefly. In my first studies on nitrogen-afterglows in 1927, I studied the spectrum of a very weak electrical discharge in glowing nitrogen. The weak discharge in those experiments was obtained from a small spark-coil, and in the new experiments from a Tesla coil (a laboratory leak-tester). When a weak discharge is passed through the old Rayleigh-Lewis active nitrogen the afterglow is quenched and the spectrum is characterized by the fourth-positive bands of nitrogen, which do not appear in the weak-discharge spectrum of non-glowing nitrogen. When a weak discharge is passed through the "auroral" afterglow, instead of quenching the glow, there appears a yellowish flash which is much brighter than the original afterglow. The spectrum of this flash contains the first-negative bands of N_2^+ and some of the first-positive bands which originate on high vibrational levels of the $B^3\pi$ electronic state of nitrogen. The spectrum of the weak discharge itself does not include either of these features, which will be recognized by those familiar with the auroral spectrum as two of the most characteristic features of that spectrum. These preliminary results show clearly that the most probable origin of the auroral spectrum lies in a proper stimulation, as by a discharge of electricity, of "auroral" active nitrogen, that is, glowing nitrogen of the type that has been studied by me in recent years.

In closing, we should like to point out, too, that the studies of the oxygen-nitrogen afterglow indicate that the light of the night sky is produced by a phosphorescence rather than a weak discharge. Perhaps the continued study of these laboratory-models will soon give definite answers to the questions of the origins of these radiations.

University of California at Los Angeles,
Los Angeles, California

MAGNETIC AND ELECTRIC INVESTIGATIONS OF THE DEPARTMENT OF TERRESTRIAL MAGNETISM OF THE CARNEGIE INSTITUTION OF WASHINGTON, APRIL 1935 TO MARCH 1936

J. A. Fleming

The work of the Department of Terrestrial Magnetism since the report published in the *Transactions* of the Sixteenth Annual Meeting followed in general the lines indicated in that report, namely: (1) Reduction and study of accumulated observational data; (2) further development of technique and apparatus to record photographically the electrical conditions and variations in the ionosphere and their investigation and correlation with other geophysical phenomena; (3) continued theoretical formulation and experimental investigation of basic aspects of nuclear physics; (4) maintenance of field-work for the purpose of secular-variation studies and of observatory-records of the changes taking place continually in the Earth's magnetic and electric fields.

The usual schedules of observations in terrestrial magnetism and electricity were continued at the Watheroo and Huancayo observatories, as also the reductions and discussions of the results obtained. Cooperation with the Apia Observatory was continued. The discussion of the Refuge Harbor report (terrestrial magnetism) of the Second MacMillan Expedition 1923-24, the data obtained at College-Fairbanks (terrestrial magnetism, aurora, and ionosphere), Point Barrow (terrestrial magnetism and aurora), Chesterfield (terrestrial magnetism and electricity, and aurora), and Little America (Second Byrd Antarctic Expedition--terrestrial magnetism and aurora) continued.

Charts of geomagnetic coordinates were constructed of the entire Earth in accordance with a resolution of the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics passed at the Lisbon meeting in 1933, as well as nomographs for obtaining geomagnetic coordinates for any point on the Globe with an accuracy of about 0°1.

An investigation of magnetic "bays" based on data from observatories distributed over the whole Earth was begun. Preliminary studies reveal a sudden reversal of direction of the assumed overhead-current to which the bays are attributed, as one approaches the zone of maximum auroral frequency.

A perminvar vertical-intensity variometer was developed and has been in continuous operation at the Cheltenham Magnetic Observatory from August 1935. It has performed satisfactorily with a scale-value of 1.5 gammas per millimeter of ordinate in the photographic record. The precision cosmic-ray meter installed at the Cheltenham Magnetic Observatory early in 1935 was maintained in operation during the past year.

A quartz-fiber magnetometer for horizontal force received from the Danish Meteorological Institute in February 1936 was carefully compared with the sine-galvanometer at Cheltenham; preliminary results indicate good agreement between the standards at Rude Skov (Denmark) and the provisional International Magnetic Standards determined by the Department.

Further studies of ionization near the ground substantiate previous conclusions that increase of ionization during thunder-storms is due to radium B and C. During the winter, observations of the effect of snow covering the ground on the ionization indicated a marked decrease with presence of the snow-blanket.

Investigations of the relationships among ions and studies of ionization near the ground were continued and additional information secured. Contrary to the findings of Pollock, the results indicate that the intermediate ions do not diminish at any vapor-pressure below saturation owing to the formation of large ions through condensation of water-vapor; their mobility was found to vary with vapor-pressure of the atmosphere in accordance with Blanc's law and their number, through the day, in a manner similar to the large-ion number and more or less opposite to the small-ion number. The intermediate ions are especially numerous during times of thunderstorms. The mobility-spectrum for the intermediate ion appears to be a narrow band. Under normal conditions practically no ions having mobilities between that of the intermediate ion and that of the large ion were found. Errors ranging from 10 to 30 per cent in small-ion counts will result if the intermediate ions collected by the small-ion counter are not taken into account.

Studies of a new experimental method for investigation of the upper atmosphere were undertaken. Calculations and laboratory-tests indicate that by projecting a modulated searchlight-beam and measuring the light scattered from sections of the high-altitude path at an observing station some kilometers distant, using a large mirror with a photo-cell and synchronized amplifier, information can be obtained regarding the molecular density and certain other characteristics of the atmosphere in the almost unexplored region from 30 to 70 km, and possibly for even greater heights.

The development of an automatic equipment for continual measurement of upper-atmospheric ionization through the whole range of heights was completed and this equipment is being tested. Manual ionospheric observations were begun at Watheroo on regular schedule, three days per week. These observations, together with the photographic records at the Huancayo Magnetic Observatory, bring out a number of new features of the upper atmosphere. The most important is that the maximum ion-density of the highest region occurs in both the Northern and Southern hemispheres during the same months; therefore, what has been previously believed to be a simple seasonal effect is shown to be much more complex--probably an annual effect. It seems probable that from the nature of the observed phenomena more definite information as to the ionization of this region may be deduced than was possible heretofore.

Compilations of the information regarding earth-currents collected at various stations in recent years, particularly during the Second International Polar Year 1932-33, has permitted us to view some of the broader aspects of the system of electric currents which circulate in the

Earth. These indicate that, during "quiet" periods, earth-currents circulate in great eddies, eight in the Northern Hemisphere and probably also eight in the Southern Hemisphere. The four near the equator in each hemisphere are roughly equally spaced in longitude. The centers of those in the Northern Hemisphere lie on a parallel of latitude not far from the Tropic of Cancer, those in the Southern Hemisphere being similarly placed relative to the Tropic of Capricorn. The entire system is fixed relative to the Sun so that any point on the Earth passes daily through all the phases of the eddies which correspond to the latitude of that point.

Satisfactory records of air-conductivity were obtained by apparatus developed at the Department of Terrestrial Magnetism on the National Geographic Society—United States Army Air-Corps Stratosphere Flight of November 11, 1935, to an altitude of 72,395 feet. It was found that the conductivity increased in a manner which may be accounted for by known factors up to an altitude of 60,000 feet, but above that point a slight decrease was observed for which no definite explanation can as yet be offered. The values of conductivity particularly at the high levels are considerably less than had been estimated from cosmic-ray measurements apparently because of uncertainties in the relationship used in making such calculations. However, the measurements are consistent with those of cosmic radiation if the relationship is modified in the manner indicated by the data as also by some laboratory experiments which have hitherto received little attention.

Measurements of the forces between the nuclei of two hydrogen-atoms when they are separated by distances of less than two ten-thousand-billionths of an inch were made. By observing the deflections of high-speed hydrogen-particles which have collided with hydrogen-nuclei in a gas-filled chamber, the attractive forces which hold together the nuclei of atoms heavier than hydrogen were measured for the first time. Without this attractive force, which is clearly one of the most fundamental forces in nature, whose existence has been previously suspected, the entire universe might consist of nothing but hydrogen. More than five years have been spent in developing the high-voltage technique to a degree of precision and control necessary for this experiment. The theoretical interpretation of the results is in progress at the Institute for Advanced Study and at the Princeton University. The possibility is indicated that the proton and the neutron are identical particles except for small changes arising from the positive electric charge on the proton. However this may turn out, the lack of quantitative knowledge regarding the "proton-proton interaction" up to the present time has been the greatest obstacle to the formulation of a satisfactory theory regarding the structure of atomic nuclei.

An outstanding event for geophysical science, particularly terrestrial magnetism and electricity, was the decision in March 1935 of the British Admiralty to construct a non-magnetic vessel to continue the magnetic survey at sea of the Carnegie. She is to be known as the Royal Research Ship Research (R.R.S. Research) and is to be given a mercantile status. Upon request of the Admiralty, plans and specifications of the Carnegie and design for instruments, as evolved during many years of the Department's oceanic work, were supplied. Upon invitation of the Admiralty, arrangements were made that William J. Peters--for many years in command of the Carnegie--go to England as consultant on the design and construction of the new vessel and of her instrumental equipment. It is expected that the vessel will be in the water early in the fall of 1936.

As in the past, every effort was made to stimulate the interest of, and to collaborate with, other organizations and investigators in all parts of the world to further research similar to that in which the Department is engaged; these efforts resulted in further coordination and closer international relations in geophysical work.

Greater details of the activities of the Department will be found in the report of the Director of the Department of Terrestrial Magnetism in Year Book 34 of the Carnegie Institution of Washington (pp. 223-267, 1935). A reprint of this report may be had upon application to the Department. A few of the papers published during the past year are as follows:

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RESEARCH IN ATMOSPHERIC ELECTRICITY AT STANFORD UNIVERSITY

Norris E. Bradbury

Professor Emeritus Joseph G. Brown is continuing his study of the analysis of the diurnal variation of the potential gradient (Terr. Mag., v. 40, pp. 413-424, 1935), obtaining interesting confirmation of his theory of the effect of turbulence and convection on the observed local gradient.

N. E. Bradbury and Russell A. Nielsen have devised a new method for the accurate determination of electron-mobilities. Results in hydrogen are being reported in the Physical Review of March 1, 1936, and experimental data have been completed for nitrogen and the rare gases. It is now proposed to extend the method to the study of electron-mobilities in air and oxygen in view of the importance of these gases in electrical discharges.

It is hoped to complete the experiment, begun by P. D. Williams, of obtaining a continuous record of the potential gradient with a captive balloon. Experiments to measure the surface space-charge and experiments to obtain a continuous record of the mobility-spectrum of atmospheric ions are also under consideration.

Stanford University,
Stanford University, California

REPORT OF THE MAGNETIC WORK AT THE ASTRONOMICAL OBSERVATORY OF MEXICO DURING THE YEAR 1935

Joaquin Gallo

The work of the Magnetic Observatory at Teoloyucan during 1935 has been limited to routine observations and the determination of the absolute magnetic values at the Observatory. Preparation for publication of the results of the past few years is in progress.

Observatorio Astronomico Nacional, Universidad Nacional de Mexico,
Tacubaya, D.F., Mexico

WORK IN GEOPHYSICS OF THE COLORADO SCHOOL OF MINES DURING 1935

D. Wantland

Instruction in geophysical prospecting by electrical methods had involved resistivity-measurements of rock specimens in the laboratory and tests for bed-rock depth along Clear Creek which flows through Golden, this being basically a placer proposition. Magnetic field-work has included an extension of a magnetic survey of Jefferson County with an Askania vertical magnetometer. Theoretical investigations have been made on the effect of the dip of layers on resistivity-depth curves. The work included a check of theory by experiments in a new compensated tank.

Department of Geophysics, Colorado School of Mines,
Golden, Colorado

RESEARCHES RELATED TO TERRESTRIAL MAGNETISM AND ELECTRICITY OF THE UNITED STATES NAVAL RESEARCH LABORATORY

H. M. Cooley

The investigation of the possibilities of locating storm-areas by means of radio static-direction recorders is being continued with stations several hundred miles apart.

An analysis of radio conditions during the past twelve years brought out the fact that, dealing with yearly averages, the radio phenomena fell in more consistently with the relative sunspot-number than with the solar constant or the terrestrial-magnetic character.

From the ionosphere-data of the National Bureau of Standards and of the Carnegie Institution of Washington, curves of the skip-distances of radio waves were prepared (Proc. Inst. Radio Eng., v. 23, p. 1492, 1935) for temperate and tropical zones during 1933 and 1934, an epoch of sunspot-minimum. It was concluded that daylight short-wave communication was controlled by the E-region in summer and by the F_2-region in winter.

U. S. Naval Research Laboratory,
Washington, D. C.

RESEARCHES AT MOUNT WILSON OBSERVATORY OF THE CARNEGIE INSTITUTION OF WASHINGTON RELATING TO TERRESTRIAL MAGNETISM

Seth B. Nicholson

Magnetic character-figures estimated from records of the horizontal intensity and declination, and solar character-figures from spectroheliograms have been reported regularly in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

The activity of the Earth's magnetic field as judged by the magnetic character-figures was only about ten per cent greater in 1935 than in 1934, although the number of sunspot-groups observed at Mount Wilson increased from 66 in 1934 to 219 in 1935. Only four of the 219 groups belonged to the old cycle and no old-cycle spot has been seen since May 24, 1935. The mean distance of the spot-zones from the solar equator was 23°.

The Sun has been photographed continuously in hydrogen-light for at least one hour each day and on several occasions continuous observations during the daylight-hours have been made on at least five consecutive days (see paper by R. S. Richardson in these Transactions). During the coming months this program will be extended to obtain a more continuous record of solar activity.

Mount Wilson Observatory, Carnegie Institution of Washington,
Pasadena, California

AURORAL AND IONOSPHERIC STATION AT THE UNIVERSITY OF ALASKA

E. H. Bramhall

The death of Professor Fuller has retarded the completion of the auroral work which was being carried on under a grant from the Rockefeller Foundation. Although we have undertaken no new photographic work in this field, we have devoted some time to the reduction of Professor Fuller's data, and have under construction charts for the graphical determination of aurora heights, which will expedite the calculation of his remaining parallactic photographs.

A two-kilowatt Kohler generator, with associated speed- and voltage-control equipment, supplied by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, is to be installed shortly and will enable us to continue the ionosphere-measurements this summer, which were interrupted in May 1935 due to the lack of a suitable power-supply.

University of Alaska,
College, Alaska

IONOSPHERE-RESEARCHES OF THE NATIONAL BUREAU OF STANDARDS

J. H. Dellinger

Measurements of the critical frequencies and virtual heights of the various regions of the ionosphere have been continued. Using both manually-operated and automatic equipment the frequency-range from 600 to 14,000 kc/sec has been covered. These measurements have extended over several years and constitute the most comprehensive set of ionosphere-data available.

Regular automatic recording of the field-intensities of several high-frequency radio emissions was begun in August 1935, furnishing data to correlate the phenomena of radio wave-propagation with those of the ionosphere.

From these two types of experimental data it was found that large increases of ionization-densities of the main regions of the ionosphere were occurring with the advancing sunspot-cycle. Two types of radio fade-outs were observed and classified.

The fundamental principles of the equipment for multifrequency automatic recording of ionosphere-heights and critical frequencies have proven to be of very great value and have been adopted by other organizations for world-wide use. The Bureau's equipment has been in operation for over three years, and has proven the practicability of automatically tuning the transmitter and receiver together. Also, the pulsing rate which is sufficient for photographic recording when used with a continuously changing radio-frequency, was proved to produce negligible interference with other radio services. The operation of the transmitter and receiver in the same room, as with the earlier fixed-frequency recorder, was proved to be convenient and economical. A recent improvement described by T. R. Gilliland (Nature, v. 134, p. 379, 1934) maintains the receiving set precisely in tune with the transmitter, the latter being provided with two oscillators, one variable and the other fixed in frequency. The fixed oscillator is set at a value equal to the intermediate frequency of the superheterodyne receiving set. The output from the antenna is either the sum- or difference-frequency. The variable oscillator of the transmitter serves also as the oscillator for the receiving set. Thus only the detector of the receiving set is required to be tuned and this tuning is not critical.

Some of the results of the ionosphere-researches of the Bureau have been published in the following papers which have appeared during the past year: Dellinger, A new cosmic phenomenon (Science, v. 82, p. 351, 1935); Dellinger, A new radio transmission-phenomenon (Phys. Rev., v. 48, p. 705, 1935); Kirby, Gilliland, Judson, and Smith, The ionosphere, sunspots, and magnetic storms (Phys. Rev., v. 48, p. 849, 1935); Kirby, Gilliland, and Judson, Ionosphere-studies during partial solar eclipse of February 3, 1935 (J. Res. Bur. Stan., v. 15, March 1936); Dellinger, A new solar radio disturbance (Electronics, v. 9, p. 25, 1936); Dellinger, Confirmation of cosmic phenomenon (Science, v. 82, p. 548, 1935); Dellinger, New cosmic phenomenon (QST, v. 20, p. 8, 1936).

National Bureau of Standards,
Washington, D. C.

PAPERS

PROGRESS-REPORT ON THE INVESTIGATION OF MAGNETIC BAYS

A. G. McNish

Magnetic bays may be defined as disturbances of the Earth's magnetism lasting for from one to several hours, the appearances of which on the magnetic records resemble the geographical features after which they are named. Although they are intriguing phenomena, little attention has been given to their study. Many investigators have remarked upon them. As early as 1882 Balfour Stewart [see 1 of "References" at end of paper] suggested that they were due to electric currents flowing in the upper atmosphere without formulating any theory as to their cause. Birkeland [2] in his investigation of magnetic disturbances in polar regions discovered that the phenomena which he called "elementary polar storms" were accompanied by bays in lower latitudes. Steiner [3] made a study of bays recorded at Ogyalla and Lubiger [4] at Samoa, the former regarding bays as due to corpuscular streams entering the Earth's atmosphere in restricted regions and the latter as being miniature storms. E. Wiechert [5] recently undertook a fairly complete study of them along the lines suggested by the Birkeland-Steiner investigations but drew his data only from middle-latitude stations. The present paper is a report on a further investigation of these phenomena which will be continued as additional data become available.

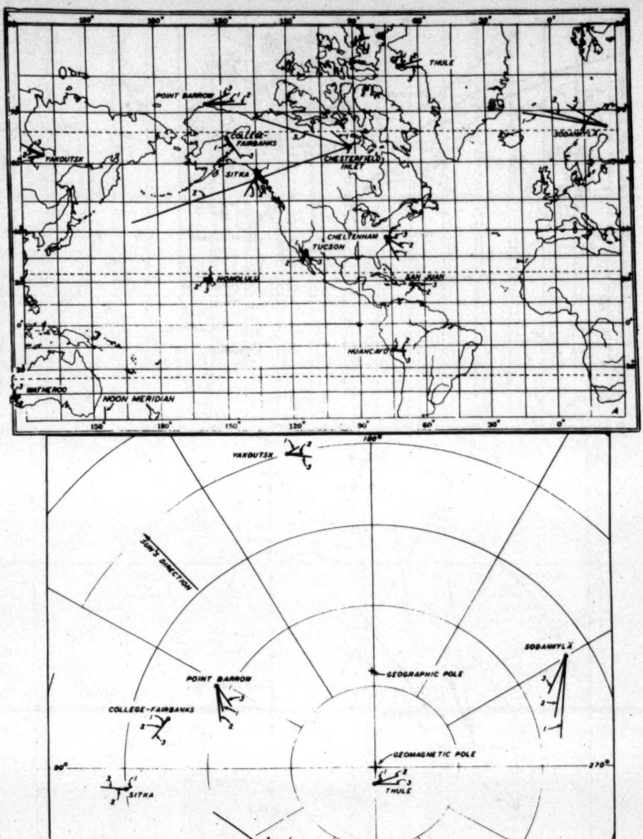
The methods employed in the present investigation closely parallel those of Birkeland. Individual manifestations of the phenomena during the International Polar Year have been selected for study in the hope that by devising adequate explanations for the particular cases the general nature of the phenomena may be comprehended. Rather than purely local phenomena, it seems from the investigation so far that bays are world-wide phenomena which are most strongly manifested in local regions. In general, certain characteristics are manifested by bays which seem to depend on latitude and local time. By the study of particular bays at various localities it is possible to clearly trace out changes in character which are associated with differences in latitude and local time.

In order to more readily visualize these phenomena the various bays selected for study have been scaled from the actual magnetograms, or their reproductions, at five-minute intervals, all times being simultaneous at the various observatories. The scaled values, reduced to the components of intensity, X, Y, and Z, were then plotted in three-dimensional perspective as departures from some arbitrarily chosen origin. Occasionally, models were constructed. In this way it was found that the locus of the end of the total magnetic vector at a given station described a loop in space during the bay which in most cases was confined to a plane in the three-dimensional space.

Some idea of the general features dependent on geographical location of the bays may be derived from the description of the appearance of these three-dimensional representations at various observatories. For one bay, which is not used in this study, the positions of the end of the total magnetic vector at the beginning and the end of the bay at De Bilt were upward and to the right with respect to its average position during the bay as viewed from the south. The extreme position reached during the bay was downward and to the left. At Cheltenham the positions at beginning and at end, corresponding to identical instants of time as for De Bilt, were downward and to the south while the extreme position was upward and to the north. At Vieques, in approximately the same longitude as Cheltenham but over 20° further south, the positions at beginning and at end were upward and to the south while the extreme position was upward and to the north. Further to the west at Tucson and Sitka the positions at beginning and at end were to the west while the extreme positions were to the east, the plane of the bay being horizontal at Tucson and tilted at Sitka so that the positions at beginning and at end at the latter station were upward.

In order to simplify the study, the bays were represented by single vectors at each station. The origin of the vectors was taken as the mid-point of the line joining the total magnetic vector at beginning and at end. From this point, lines were drawn to selected extreme positions of the bays. These lines constitute vectorial representations of the departures in magnetic intensity at various stages of the bays. The representative vectors are taken for simultaneous times at all observatories.

It has not been possible as yet to reach any definite conclusions relative to the proportion of the magnetic departures due separately to magnetic origins inside and outside the Earth,


150°
180°
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120°
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30°
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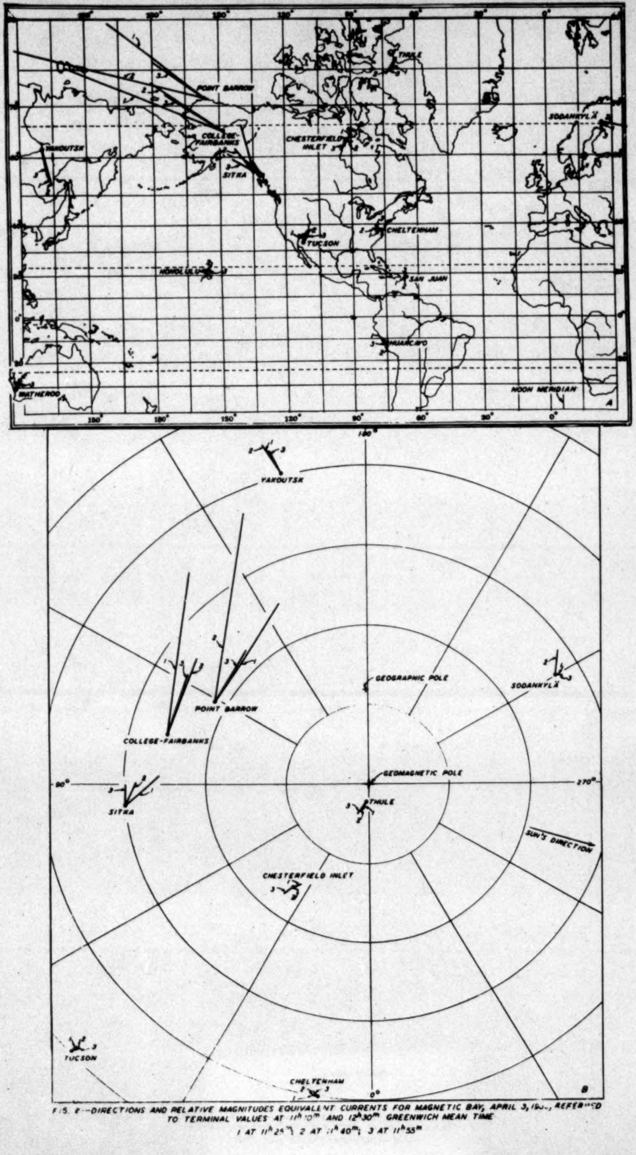
THULE
POINT BARROW
SODANKYLÄ
COLLEGE-FAIRBANKS
YAKOUTSK
CHESTERFIELD INLET
SITKA
CHELTENHAM
TUCSON
HONOLULU
SAN JUAN
HUANCAYO
WATHEROO
NOON MERIDIAN
A
180°
YAKOUTSK
SUN'S DIRECTION
SODANKYLÄ
POINT BARROW
GEOGRAPHIC POLE
COLLEGE-FAIRBANKS
90°
GEOMAGNETIC POLE
270°
SITKA
THULE
CHESTERFIELD INLET
TUCSON
CHELTENHAM
0°
B
1
2
3

FIG. 1—DIRECTIONS AND RELATIVE MAGNITUDES EQUIVALENT CURRENTS FOR MAGNETIC BAY, MARCH 20, 1933, REFERRED TO TERMINAL VALUES AT 1^h00^m AND 3^h00^m GREENWICH MEAN TIME

1 AT 1^h30^m; 2 AT 1^h45^m; 3 AT 2^h00^m


POINT BARROW
COLLEGE-FAIRBANKS
SITKA
YAKOUTSK
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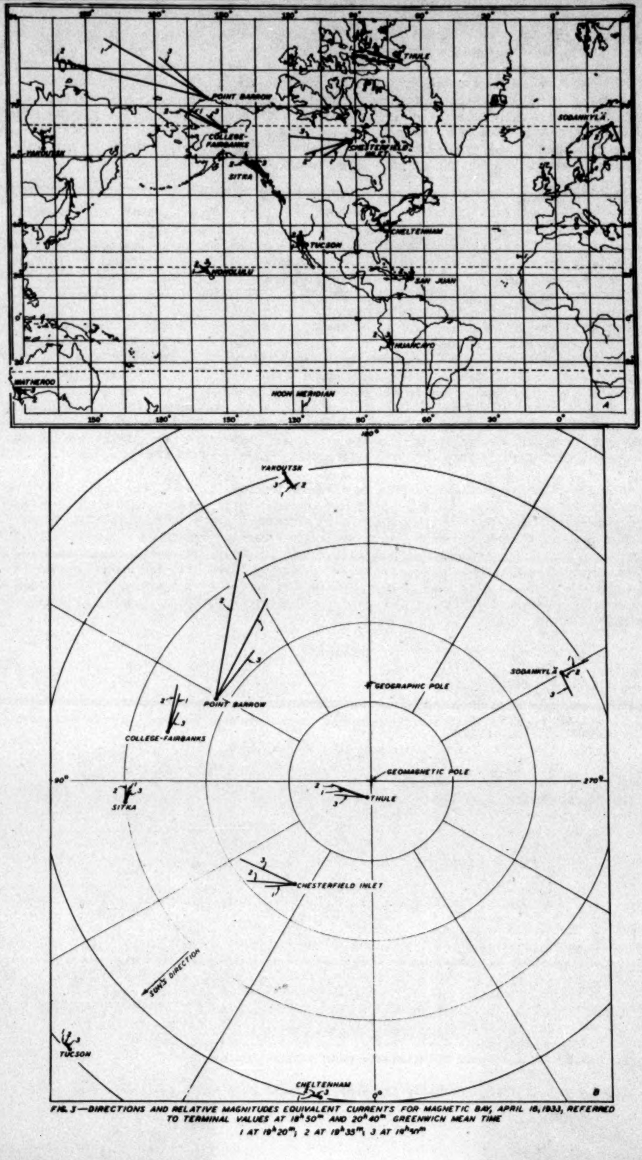
CHESTERFIELD INLET
SODANKYLÄ
CHELTENHAM
TUCSON
HONOLULU
SAN JUAN
HUANCAYO
WATHEROO
NOON MERIDIAN
A
GEOGRAPHIC POLE
GEOMAGNETIC POLE
SUN'S DIRECTION
180°
90°
270°
0°
B

FIG. 2.--DIRECTIONS AND RELATIVE MAGNITUDES EQUIVALENT CURRENTS FOR MAGNETIC BAY, APRIL 3, 19[illegible], REFERRED TO TERMINAL VALUES AT 11^h10^m AND 12^h30^m GREENWICH MEAN TIME

1 AT 11^h25^m; 2 AT 11^h40^m; 3 AT 11^h55^m


THULE
POINT BARROW
COLLEGE-FAIRBANKS
CHESTERFIELD INLET
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WATHEROO
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180°
YAKOUTSK
GEOGRAPHIC POLE
POINT BARROW
COLLEGE-FAIRBANKS
GEOMAGNETIC POLE
90°
270°
SITKA
THULE
CHESTERFIELD INLET
SUN'S DIRECTION
TUCSON
CHELTENHAM
0°
B

FIG. 3—DIRECTIONS AND RELATIVE MAGNITUDES EQUIVALENT CURRENTS FOR MAGNETIC BAY, APRIL 16, 1933, REFERRED TO TERMINAL VALUES AT $18^h 50^m$ AND $20^h 40^m$ GREENWICH MEAN TIME

1 AT $19^h 20^m$; 2 AT $19^h 35^m$; 3 AT $19^h 50^m$

although it is quite evident from the relative magnitudes of the horizontal and vertical components of the changes in magnetic intensity that both internal and external causes are active. A tentative assumption has been made that the magnetic changes in the horizontal plane are caused by current-sheets in the ionosphere. Thus it is possible to represent the direction and intensity of such currents by vectors perpendicular to the magnetic vectors and proportional to them. These current-vectors are illustrated in Figures 1 to 3. No definite scales are given since it is not possible to state the magnitudes of the currents except in accordance with the tentative assumption mentioned above. The current-vectors pictured are probably similar to the true current-vectors in both direction and relative magnitude.

Several features are evident from the Figures. The intensities of the currents are very much greater in regions near the auroral zone than at higher or lower geomagnetic latitudes. This is particularly well brought out by Figures 1B, 2B, and 3B which are plotted according to the geomagnetic coordinates. Owing to the small number of the observatories employed, it is not possible to accurately define the systems of the apparent currents. Referring to Figure 1A, it appears that a strong current flows westward along the auroral zone from Sodankylä to Chesterfield Inlet and then circles around across Sitka, Tucson, Cheltenham, and Huancayo, apparently closing across Europe. Certain aspects of the current-system for this same bay are more clearly brought out by Figure 1B, particularly the southward direction of the current over Sitka. Considering the auroral region as the main artery of flow, it appears that the return current also passes over the geomagnetic pole. The most dense flow appears to be on the side of the Earth away from the Sun. Similar features are revealed in Figures 2A and 2B, the most dense flow being in the auroral region on the dark side of the Earth which, because of a difference in time of occurrence, is over Point Barrow and College-Fairbanks. The current-system shown in Figures 3A and 3B appears to be anomalous. However, the directions of the currents at Point Barrow, Yakoutsk, and Sodankylä, as shown best in Figure 3B, suggest a very dense flow over the region between these three observatories, fitting into the general conception derived from the other bays.

To draw far-reaching conclusions from such meager data is unwise. It appears quite evident that most bays may be explained as due to intense westward currents along the auroral zone near the midnight meridian associated with returning currents over the remaining portions of the Earth. Such a concept seems in keeping with the quite generally recognized tendency for bays with increasing horizontal intensity (positive bays) to occur around midnight in middle latitudes and for bays with decreasing horizontal intensity (negative bays) to occur around midday in middle latitudes. What could give rise to such a system of currents is a matter of conjecture which it seems should be reserved until the time when the general aspects of the current-system are more completely known.

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[2] The Norwegian Aurora Polaris Expedition 1902-1903, Christiania, 1913.
[3] Terr. Mag., v. 26, pp. 1-14, 1921.
[4] Dissertation, Göttingen, 1924.
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IMPROVED INSTRUMENTS AND METHODS FOR MAGNETIC MEASUREMENTS

H. E. McComb

1. Within the past year a number of important advancements have been made in connection with improvement of magnetic standards at the magnetic observatories of the United States Coast and Geodetic Survey (referred to hereafter as CGS), especially at Cheltenham. The new test-and-comparison building and the new absolute-observatories, all well equipped with suitable instrument-piers, correct electric lighting, etc., have made it possible to carry out extensive investigational programs by members of the observatory-staff and have greatly stimulated cooperative investigations with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (referred to hereafter as CIW). All of this work is leading to the establishment of better magnetic standards and tends to eliminate much duplication of effort.

2. CIW sine-galvanometer--Probably the most important step which has been taken in many

years toward the improvement of magnetic standards of the Survey was that of the transfer of the CIW sine-galvanometer from the Standardizing Magnetic Observatory of CIW at Washington to Cheltenham, to be operated as a standard horizontal-intensity instrument in place of the magnetometer previously used as standard there. [This transfer was made possible only after the installation of suitable electric power-supply at Cheltenham several years ago.] Special piers were constructed in both of the absolute-observatories so that simultaneous intercomparisons with interchange of stations might be accomplished with comparative ease. In addition to the CIW sine-galvanometer, a special constant-temperature cabinet was constructed by CIW and installed on special piers in the Observatory. This cabinet houses the standard Eppley cells, the standard resistance, the potentiometer, and the control-circuit supplied by CIW, all of which have been calibrated at the National Bureau of Standards, and the batteries for supply-current. Every possible precaution has been taken in carrying out this work in order to insure a reliable standard not only for comparison of the instruments of CGS and CIW but for international comparisons as well. The instruments have been in successful operation for several months. Observations with the standard magnetometer of the Observatory have been reduced in frequency to one set every two months. All of the preliminary CIW sine-galvanometer work, including the detailed comparisons and transfer of the provisional International Magnetic Standards of CIW to Cheltenham, were carried out by Messrs. Forbush, Johnson, and Green of CIW.

3. Earth-inductor comparisons--Comparisons of CIW standard earth-inductor and the Observatory earth-inductor (using two separate coils on the latter) are under way at the present time. It is expected that this series of observations, which is to extend over a period of several months, may throw some light on the cause of irregular base-lines of the vertical-intensity variometers at the Cheltenham Observatory. Using a cathode-ray oscillograph furnished by CGS, E. A. Johnson of CIW has made a study of the output-characteristics of various earth-inductors at Cheltenham in an effort to investigate possible defects in design or construction.

4. Orientation of variometers--The comparisons and tests of CIW sine-galvanometer brought out the fact that there were some variations in base-line differences between the horizontal-intensity variometers at Cheltenham which could be accounted for partly on the assumption that the recording magnets were not normally in the prime-vertical and parallel. Magnetic meridians have been established in the variation-rooms, and after a series of careful tests and adjustments the recording magnet of the Toepfer horizontal-intensity variometer has been placed in the prime-vertical. Tests for the magnetic level of the recording magnets of all vertical-intensity variometers at Cheltenham have also been made by the magnetic method and in no case has the inclination exceeded 1°5. This work was carried out by Messrs. Ludy and Hartnell of CGS.

5. Perminvar-variometer--At CIW, Mr. McNish has devised a vertical-intensity variometer in which pivot and knife-edge supports are eliminated. It has been constructed in experimental form from CIW instrument-parts and from perminvar obtained from the Bell Telephone Laboratories by CGS. It has been operated for various periods on a special pier at Cheltenham and the results are being compared with other variometers. The indications are that the instrument will prove to be satisfactory and, it is hoped, will solve the problem of vertical-intensity variometer-suspensions.

6. Vertical-intensity-variometer metallic suspensions--It has been suggested many times that the use of metallic ribbons in place of pivots or knife-edges for support of the recording magnet of the vertical-intensity variometer might result in more uniform performance of this type of instrument. During the past careful tests were made with such a system but the results were not satisfactory. Filaments, both flat and round, of the following materials were tried: (a) Phosphor bronze; (b) Allegheny metal (various sizes); (c) copper-beryllium; (d) Swedish steel (flat only); and (e) single silk-filaments. In every case the zero-point was not constant but always shifted to a new value for large deflections, the new value always being in the direction of the deflection, thus indicating a permanent strain on the suspension. As a constant zero-point is one of the prime requisites of a variometer, this defect alone in metallic suspensions was sufficient cause for discontinuance of the tests. It should be stated in passing that the instrument-work on these suspensions and supports was of the very highest order. These tests were carried out by Dr. J. W. Joyce while stationed at the Cheltenham Observatory.

7. Askania variometer--An Askania magnetic field-balance, loaned by the United States Bureau of Mines, was modified for photographic recording and tested at Cheltenham for temperature-compensation and performance for a short period. The method of temperature-compensation used on this type of instrument is probably superior to all others in present use.

8. Comparison of vertical-intensity variometers--During the year a 42-day comparison of four variometers of the pivot and knife-edge types was carried out by George Hartnell of CGS and the results indicate that satisfactory performance was obtained for the four instruments for

this period at least. The resulting magnetograms show surprising agreement. The comparison of these variometers is being continued. In connection with some of these tests it was found that the scale-value of the la Cour variometer-magnet under test is practically constant at all usable ordinates, which is not true of instruments of the Eschenhagen type which have been tested.

9. La Cour magnets--Using a special magnetometer equipped with a Gauss eyepiece, R. E. Gebhardt of CGS has determined the angles between the magnetic axis and the plane of the magnet-mirror on four la Cour magnets which had been used at the College-Fairbanks Polar-Year Observatory. A knowledge of this angle is essential for the proper orientation of a vertical-intensity recording magnet with respect to the horizontal. The information obtained in these tests was also used in connection with the reduction of some of the Polar-Year data.

10. Temperature-lag in variometers--It was thought at one time that, due to the operation of the la Cour vertical-intensity magnets in a partial vacuum, the temperature within the magnet-chamber might lag behind that observed just outside the chamber. Several tests indicate that this temperature-lag is not serious. With the temperature changing at the rate of 12° C per hour the maximum lag observed was only about 1° C. Such sharp temperature-changes are never experienced even in moderately insulated observatories.

11. Bifilar horizontal-intensity variometer--A Toepfer horizontal-intensity variometer has been provided with a bifilar silk-suspension and preliminary tests indicate that it is entirely satisfactory. It is expected that it will eventually replace the unifilar quartz-suspension variometer now in operation at Cheltenham.

12. Declinometer scale-value tests--R. E. Gebhardt and the author have completed some rather exhaustive tests of the standard declination scale-value equations by direct comparison of the angle of rotation of a variometer-mirror mounted on a divided circle and the corresponding motion of a spot of light reflected from this. A collimating lens of proper focal length was mounted in front of the mirror and at such a distance from the scale which would provide a scale-value of one minute of arc per millimeter on the scale. The vernier of the circle permitted readings to 10", estimating to 5". The tests prove that the scale-value equation in common use is sufficiently accurate for all practical purposes. In addition to the above tests, the scale-value was checked by magnetic deflection-methods using a standard magnetic deflector of known magnetic moment and found to be in close agreement with the above. Also using the above set-up, the coil-constants of three Helmholtz coils were determined by the usual electrical method and found to be in close agreement with the constants as computed from the dimensions of the coils. The tests remove all doubt about the accuracy of either method of determining scale-values.

13. Improvement of magnetometers--Within the past year a large amount of work has been done in improving the optical systems of magnetometer-magnets. Through cooperation with the National Bureau of Standards, a special ruling diamond has been obtained and a suitable dividing engine has been developed for ruling fine lines on magnet-windows and on telescope-diaphragms. In addition, all magnets are being chromium-plated.

14. Unequal deflections in intensity-measurements--It has been pointed out that serious errors may arise in computing the horizontal intensity from mean magnetic deflections if the deflections at corresponding east and west distances differ by large amounts. Steps are being taken to provide attachments for observatory-magnetometers which will permit the observer to adjust the magnetometer at the beginning of a series so that the deflections shall be practically equal and thus reduce to a negligible quantity the error from this source.

15. Electrical methods--The work on electrical methods, started over a year ago by E. A. Johnson while in CGS, is being continued by him along similar and extended lines at CIW.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SUNSPOT-ACTIVITY AND RADIO TRANSMISSION FADE-OUTS

R. S. Richardson

This paper contains a description of solar observations made at the Mount Wilson Observatory of the Carnegie Institution of Washington to investigate a possible connection between sunspot-activity and a series of high-frequency radio transmission fade-outs occurring at intervals of about 54 days. These observations were made at the request of Dr. J. H. Dellinger, Chief of the Radio Section of the National Bureau of Standards, who first called attention to the phenomenon

(Phys. Rev., v. 48, p. 705, 1935, and Science, v. 82, p. 351, 1935). The effect, as originally reported, consists of a sudden and complete disappearance for about 15 minutes of all high-frequency radio transmission over the illuminated half of the Earth. The first fade-outs reported occurred in 1935 on March 20, May 12, July 6, and August 30. A later report was received of a fade-out in the eastern part of the United States on November 28, 1934. This was not supported by data from elsewhere, however. Dr. Dellinger urged that as nearly continuous observations as possible be made of the Sun from October 21 to 25 when the next manifestation should take place.

The spectroheliograms made at Mount Wilson as part of the routine daily program were examined on the dates in question and for about a week preceding each fade-out for unusual sunspot-activity. Nothing was found for the first fade-out on March 20, and our plates are defective for the one on May 12. For the next two on July 6 and August 30, however, we were fortunate in having exposures made while the fade-outs were actually in progress. On July 6 a hydrogen-flocculus in the vicinity of a spot-group near the southeast limb of the Sun changed in form and decreased in intensity during the time of the observations. It is impossible to estimate accurately its maximum intensity, but it was probably not large since calcium-spectroheliograms taken earlier show no great activity. On August 30 a rather spectacular eruption of bright hydrogen occurred over a spot near the central meridian. The spectroheliograms for the fade-out reported by a single observer on November 28, 1934, are of considerable interest. Again we were fortunate in having plates taken as part of the routine work during the actual time of the fade-out. The hydrogen-spectroheliograms showed a fairly bright flocculus over a sunspot but no change could be seen on successive exposures. But in the calcium-spectroheliograms taken 30 minutes later the flocculus had become very bright, and evidently an eruption of considerable intensity had occurred near this region. When the Sun is observed for about half an hour each clear day, as is our routine solar work, we may expect to photograph about ten flocculi such as these in one year at this phase of the solar cycle.

Hydrogen-spectroheliograms were taken at Mount Wilson from October 21 to 25 at intervals of about eight minutes. The only important change observed occurred on October 24, when a faint flocculus showed a considerable increase in brightness in about 15 minutes. Dr. Dellinger (Science, v. 82, 548, 1935) reported that on October 10 there was a general improvement in radio transmission on the higher frequencies, and by October 21 to 23 the upper limit of frequency had reached the highest value ever observed by the National Bureau of Standards. Then on October 24 the upper limit of frequency dropped to half its value on the preceding days, and on October 25 and succeeding days returned to its previous high value.

The program from December 14 to 18, the time assumed for the next fade-out, was essentially the same as before, except that the hydrogen-spectroheliograms were taken in the afternoon with a solar image 2 cm in diameter instead of a 5-cm image. This reduced the exposure-time from about four minutes to one minute and enabled observations to be made as late as 30 minutes before sunset. The spectroheliograms were taken as rapidly as possible from about 16^h 30^m to 24^h 30^m, and it is believed that any sunspot-activity occurring between these hours would not have been missed.

Two changes of moderate intensity were noted on December 15, but nothing unusual was observed until the afternoon of December 16. At 22^h 10^m a bright flocculus which was not there two minutes earlier was observed near a large spot-group at 50° west, 23° south. It increased in intensity for about 13 minutes, then began to fade rapidly, and had vanished at 22^h 38^m. At maximum this flocculus was equal in brightness but only about half as large as that of August 30, 1935. On the first plate taken next day at 16^h 09^m another brilliant eruption was seen over the same spot-group. Hydrogen-spectroheliograms taken as part of the routine program on December 23 from 17^h 57^m to 18^h 05^m showed a bright flocculus near a spot-group at 36° west, 28° south. Another eruption occurred over the same region between 22^h 42^m and 22^h 49^m and was gone eight minutes later.

Dr. Dellinger, in a letter to the writer dated December 27, 1935, stated that no very striking radio phenomena had been reported from December 14 to 21. The only anomalies he thought worth mentioning took place on December 17 and 23. On December 17 the Bureau's ionosphere-observations showed a noo (E.S.T.) value for the F_2 critical-frequency of 9000 kc/sec as compared with an average of 11,000 kc/sec on December 16 and 18. On December 23 between 17^h 40^m and 18^h 40^m distant statious and ionosphere-echoes received at the Bureau were very weak, and station W8XAL on 6060 kc/sec received via the E-layer, was completely out. They returned slowly to normal during the following hour.

The latest fade-outs received by Dr. Dellinger were on February 6, 14, and 17, 1936, the one on the 14th being particularly striking and noticed by many observers in many places. The one on the 17th was not of the sudden type but a general lowering of the critical frequencies and increase of the virtual height of the F_2-layer. Unfortunately, we were unable to observe at Mount Wilson from February 10 to 19, inclusive, owing to cloudy weather. Hydrogen- and calcium-spectroheliograms taken on February 6 and 7 showed several cases of moderate sunspot-activity over widely separated areas on the Sun, but nothing of an exceptional nature. With so many active regions on the disc, however, it is not improbable that other and more spectacular eruptions may have occurred on these days. Assuming February 14 to be the time of the last fade-out, the next one may be expected some time from April 6 to 11. Another series of continuous observations will be made during this time, weather permitting. [In this connection, see Terr. Mag., v. 41, pp. 197-198, 1936.]

The special solar observations were carried on for about nine days, on each of which the Sun was photographed almost continuously for about eight hours, making a total of 67 hours of observation. Three bright hydrogen-eruptions were noted during this time. The routine solar observations from October 1 to December 31 totalled 65 hours and seven eruptions of about the same brightness were recorded. Thus the number observed on the special days selected because of their possible connection with anomalies in radio transmission was only about half that which might have been expected.

Bright hydrogen-eruptions are not an exceptionally rare or unusual form of sunspot-activity, but only appear to be so due to their ephemeral nature and the lack of continuous observations. A special observing program made at any time when spots are numerous would probably show an average of one eruption for every twelve hours of continuous observations.

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SOME OBSERVATIONS ON THE DIURNAL VARIATION OF THE VERTICAL INTENSITY OF THE EARTH'S MAGNETIC FIELD

Victor Vacquier

(Abstract)

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The purpose of this investigation was to find out the amount by which magnetic diurnal-variations vary on individual days between points only a few hundred miles apart, and to study the manner in which the magnitude of these local irregularities depends upon the separation of the points of observation.

Observations of the diurnal variation of the Earth's magnetic vertical intensity were made by the exploration troops of the Gulf Research and Development Corporation. The sensitivity of the Schmidt Askania variometers was three gammas per scale-division. Eye-readings on a variometer kept at the base-station were taken every ten minutes during the hours the troop was operating in the field. The probable error of field-observations, and therefore also of the diurnal-variation measurements, was about one gamma.

The points at which the diurnal variation was measured were geographically located as follows: Troop I, latitude 38°6 north in longitude 102°5 west; troop III, latitude 31°0 north in longitude 89°3 west; troop IV, latitude 34°3 north in longitude 101°3 west; troop V, latitude 34°4 north in longitude 96°8 west; troop VII, latitude 35°3 north in longitude 98°2 west.

To compare two diurnal-variation curves, the curves were read every half-hour local time and subtracted. The mean difference for the day was then subtracted from each half-hourly difference. The resultant curve represents the residuals obtained by subtracting the diurnal curves after shifting them vertically so that their average ordinates for the day were made to coincide. Examination of these residual curves shows that for points only 260 miles apart differences of one-half of the total diurnal range are not uncommon. The sum of the absolute values of the half-hourly differences was then taken over all days on which the amplitude of the diurnal curves was smaller than 35 gammas (1 gamma = 0.00001 C.G.S. unit), divided by their total number, and multiplied by 0.845, thus obtaining the probable difference. If one assumes that the differences between the diurnal variations at the two geographic points considered are due to random fluctuations, one can expect that as many of these will be greater than the probable difference as will be smaller.

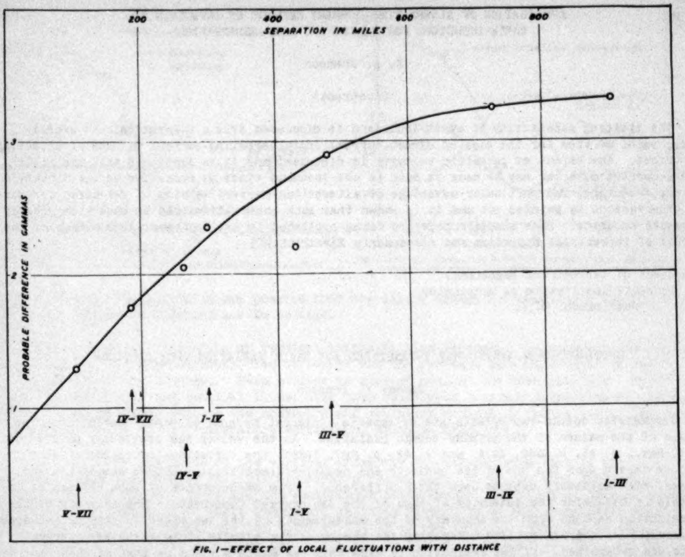

FIG. 1—EFFECT OF LOCAL FLUCTUATIONS WITH DISTANCE

The probable differences are plotted on Figure 1 for the available sets of two geographic points as a function of their separation in miles. This Figure, which is based on the comparison of 303 sets of two diurnal-variation curves, shows that the contribution of the fluctuations of local character reaches a constant value of 2.5 gammas at a distance of about 800 miles. If one compares the mean curve of the vertical-intensity variation for July 1925 at Tucson, between 8^h 30^m and 17^h with a horizontal line by the procedure used in this investigation, a probable difference of 4.5 gammas is obtained. This roughly indicates that 56 per cent of the magnetic vertical variation is of local origin.

It is intended to amplify this study with the data of Cheltenham and Tucson observatories.

Gulf Research and Development Corporation,
Pittsburgh, Pennsylvania

MAGNETIC ANOMALIES IN THE CAROLINA COASTAL PLAIN

G. R. MacCarthy

(Abstract)

A magnetic survey of southeastern North Carolina and northeastern South Carolina carried out with an Askania vertical variometer shows that the Atlantic Coastal Plain of this region contains many linear magnetic anomalies with a general northeast-southwest trend. These linear anomalies are of both positive and negative sign relative to the regional average. Many localized or "point-highs" were also found. These point-highs seem to be associated with the elliptical depressions or "bays" which are common in this general region. [This paper will appear in full in an early issue of the Journal of Geology.]

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APPLICATION OF ALTERNATING-CURRENT METHODS OF DETECTION TO EARTH-INDUCTORS FOR MARINE AND LAND OBSERVATIONS

E. A. Johnson

(Abstract)

The limiting sensitivity of earth-inductors is discussed from a theoretical and experimental point of view for the case of direct-current and alternating-current methods of detecting the output. The effect of parasitic voltages is discussed and it is concluded that the alternating-current detector may be made as much as one thousand times as sensitive as the direct-current detector. The particular advantage of alternating-current methods of detection for marine observations is pointed out and it is shown that such observations can be made with greatly increased accuracy. [The complete paper is being published in the September 1936 number of the Journal of Terrestrial Magnetism and Atmospheric Electricity.]

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UNIDIRECTIONAL COSMIC-RAY INTENSITIES AND THEIR VARIATION WITH LATITUDE

Thomas H. Johnson

Geomagnetic cosmic-ray effects are of especial interest because of their bearing upon the problem of the nature of the primary cosmic radiation. As the writer has previously pointed out (Phys. Rev., v. 45, p. 569, 1934, and v. 48, p. 287, 1935), the variations of intensity with latitude depend upon the sum of the positive and negative electrically-charged components and the west-east asymmetry depends upon their difference. From measurements of both effects it is possible to determine the intensity of each of the two charged components. The accuracy of the determination depends upon the accuracy of the measurements of the two magnetic effects and upon the accuracy of the assumptions underlying the theory of the effects, from which the energy-limits are determined. If the assumption is made that the Earth's field is that of an eccentric dipole, the theory of Lemaitre and Vallarta (Phys. Rev., v. 49, p. 719, 1936, and previous articles referred to therein) may be applied, but on this basis inconsistencies in the estimates of the composition of the primary cosmic radiation arise when the experimental results from different longitudes are considered. Such inconsistencies appear to be greater than can be accounted for by the experimental errors and they lead to the suspicion that local anomalies in the Earth's magnetic field, not specified by the field of the dipole, are having an important influence on the observed geomagnetic cosmic-ray effects. This suspicion constituted one of the reasons for making unidirectional measurements of the cosmic-ray latitude-effect, for it was realized that rays from the vertical direction should be more subject to such local effects than those incident from other directions. There was also the need for quantitative measurements of the latitude-effect from particular directions, notably the vertical direction, in terms of the sensitivity of the coincidence-counter train, for with this instrument there is no correction to be made for the absorption of the cosmic rays in a lead shield such as is used in the electroscope-technique and it is with this instrument that asymmetries are measured.

The unidirectional cosmic-ray-intensity meter developed by the writer and Dr. Donald N. Read is suitable for mounting on board ship and is capable of making unattended voyages of considerable duration. It embodies eight separate instruments, each giving its own independent record. In December 1935 this instrument completed its first successful voyage on the Grace Line steamship Santa Barbara from New York to Valparaiso and return, north and south along the 75th meridian. On this voyage six of the instruments were arranged in duplicate for recording rays from three directions, namely, the vertical and at 45° on either side of the vertical in the plane perpendicular to the meridian. Three of these instruments brought back successful records. The two additional instruments were arranged for recording showers of cosmic rays generated as a result of nuclear encounters in a block of lead. One of these instruments was successful.

The counters were mounted in a sealed box which was swung freely on two mutually perpendicular horizontal axes allowing the apparatus to maintain a fixed direction in space regardless of the pitch and roll of the ship. The coincidences, selected and amplified by suitable vacuum-tube circuits, were transmitted through a flexible cable to a set of recording dials mounted inside of another box. These dials were photographed at regular intervals by an automatically

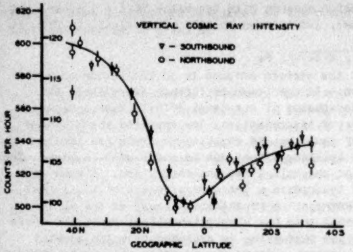


FIG. I—VERTICAL COSMIC-RAY INTENSITY VERSUS GEOGRAPHIC LATITUDE

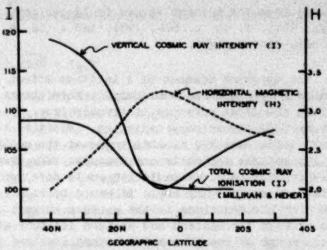


FIG. 2—VERTICAL COSMIC-RAY INTENSITY, AVERAGE COSMIC RADIATION, AND MAGNETIC HORIZONTAL COMPONENT VERSUS GEOGRAPHIC LATITUDE

operated camera. The apparatus was powered from the ship's dynamo and regulating devices were used to compensate the fluctuations in voltage.

Figure 1 shows the variation of vertical intensity with latitude. In reducing the results hourly readings have been corrected for barometer and the averages have been taken of the 24 hours from midnight to midnight. This average is plotted against the noon latitude. The probable errors, represented by the vertical lines, have been calculated from the dispersion of the hourly readings. The agreement between the northward and southward voyages is indicative of the absence of systematic errors due to temperature-variations, aging effects, etc.

In Figure 2 the variation of the vertical intensity is compared with that of the total intensity as recorded by one of Millikan and Neher's (Phys. Rev., v. 47, p. 205, 1935) electroscopes with a 10-cm lead shield. There are two conspicuous differences. The vertical intensity passes through a sharp minimum at 5° north geographic latitude instead of on the geomagnetic equator at 12° south geographic latitude; and the total variation of the vertical intensity is about 20 per cent compared with seven or eight per cent variation in the total intensity. The constant high-latitude value seems not to have been reached at either New York or Valparaiso. Considering the second difference first, a greater latitude-effect was to have been expected for the vertical radiation since it was already known that the magnetically deviable component was less penetrating than the average radiation. Rays passing through the atmosphere along the short vertical path would thus be represented in greatest proportion by the soft component. The ratio between the latitude-effects measured by the two techniques is quantitatively consistent with the known values of the absorption-coefficients of the average radiation and of the magnetically deviable component. In regard to the position of the minimum of the intensity of vertical radiation, this coincides with the position of maximum horizontal magnetic field plotted along the same course as represented in Figure 2. This is a striking example of the importance of the local field in determining the energy-limits of the radiation which reaches the Earth's surface from the vertical direction. These rays experience much of their bending during the last few thousand miles of their trajectories and they have no opportunity to strike an average of the local anomalies. Inclined rays which make up most of the intensity measured by the electroscope have much more of a tendency to spiral around the Earth and back and forth between the Northern and Southern hemispheres. Thus their deflections are more characteristic of the average field of the Earth, represented by the eccentric dipole.

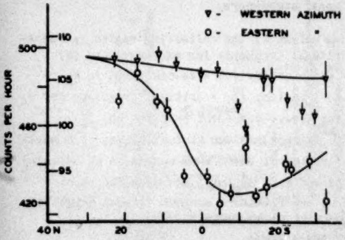


FIG. 3—LATITUDE-EFFECTS OF RAYS INCIDENT AT 45° FROM PLANE OF THE MERIDIAN IN EASTERN AND WESTERN AZIMUTHS

The results obtained with the coincidence-trains pointing at 45° from the vertical are represented in Figure 3. These results are presented not without some apology, for a slight temperature-effect was found in one of these trains, due to some faulty resistors, and this probably had an effect on the results at the extreme northern end of the voyage. However, the remaining data are probably reliable within the limitations of the relatively high probable errors. The greater latitude-effect in the eastern azimuth, shown by the lower curve, is consistent with the asymmetry previously found at the equator. The magnitude of this asymmetry deduced from the present values is 14 per cent, which accords with the value 14.5 ± 1.6 per cent (Phys. Rev., v. 45, p. 569, 1934, and v. 48, p. 287, 1935) found in 1933 at sea-level in Peru at the same zenith-angle.

The apparent absence of a latitude-effect in the western azimuth is an indication of a phenomenon which deserves considerably more attention. If confirmed by further experiments this will be the first directly observable proof of the absence of sea-level effects from a negative component of the primary radiation. Positive rays of the relatively low energies which become magnetically excluded at this angle at the equator would not be expected to reach sea-level with any appreciable intensity and hence no very great latitude-effect can be attributed to them. The corresponding negative radiation would have two and one-half times the energy and, if such were present in the primary beam, it would be expected to produce a latitude-effect similar to that found for the positives in the eastern azimuth. Perhaps a more important cause of the difference between the eastern and western latitude-effects than the absorption-effect mentioned above is the range of energies which become involved in the band which is excluded from the equator but not from the higher latitudes. At 45° on the western side of the meridian this band includes positive rays in the range from 0.24 to 1.0×10^{10} volts, whereas on the eastern side of the meridian at the same angle the range is 0.26 to 2.5×10^{10} volts. For negative rays the azimuths are reversed.

The results obtained with the shower-counting arrangement are not shown but it may be remarked that these results were concordant with observations made in Pennsylvania and Mexico in 1934 (Phys. Rev., v. 47, p. 318, 1935). The latitude-effect for the showers is less than that for the vertical radiation and no appreciable change of intensity begins to show until a latitude of less than 20° is reached. The total latitude-effect for the showers is of the order of five per cent. This result has the interpretation that the rays which produce the showers are less affected by the Earth's field than the average radiation. They may be produced by a component of the primary radiation which for a given magnetic rigidity is less penetrating as regards the atmosphere than is the case with the average radiation, or it may be that the showers are produced with higher probability by the more energetic radiation.

The results reported here have been obtained under grants from the Carnegie Institution of Washington, to whom acknowledgment is gratefully made. We are also indebted to the Grace Line, Incorporated, for permission to install the apparatus on its ship.

Bartol Research Foundation, Franklin Institute,
Swarthmore, Pennsylvania

NEW FACTORS IN INVESTIGATION OF THE IONOSPHERE

L. V. Berkner, H. W. Wells, and S. L. Seaton

The ionized upper atmosphere was originally conceived as a single ionized region or ion-bank existing above about 80 km to explain phenomena of terrestrial-magnetic variation and long-distance radio-wave propagation. Following direct experimental evidence of the existence of such a region, it was found that the ionization-pattern was much more complex than originally imagined. Experiment showed that reflections observed with different radio frequencies fell into two or more classifications with respect to virtual height, and lead to the conclusion that these represented major regions of ionization in the upper atmosphere.

As the observing frequency is changed, the virtual height of the reflecting region is represented by the record shown in Figure 1, where $f^x_{F_2}$ = critical frequency for extraordinary (x) wave-component in F_2-region, $f^o_{F_2}$ = critical frequency for ordinary (o) wave-component in F_2-region, $f^x_{F_1}$ = critical frequency for x wave-component in F_1-region, $f^o_{F_1}$ = critical frequency for o wave-component in F_1-region, f^x_E = critical frequency for x wave-component in E-region, f^o_E = critical frequency for o wave-component in E-region, $h^o_{F_2}$(min) = minimum virtual height of o wave-component in F_2-region, $2h^o_{F_2}$(min) = first multiple reflection of the o wave-component at $h^o_{F_2}$(min) caused by the signal making two complete paths from the Earth to $h^o_{F_2}$(min) and back, $h^o_{F_1}$(min) = minimum virtual height of o wave-component in F_1-region, and f^o_E(min) = minimum virtual height of o wave-component in E-region. The ion-density necessary to reflect the o wave-component at normal incidence can be calculated from the well-known expression

$$N = 1.24 \times 10^{-8}(f^o)^2 \qquad (1)$$

The relation between the frequency of the o and x wave-components which are reflected from the same ion-density is given by

$$f^x = \sqrt{(f^o)^2 + (f_H/2)^2} + f_H/2 \qquad (2)$$

where f_H is the precession-frequency $He/2\pi mc$, H being the intensity of the Earth's magnetic field at the level of reflection. In such a dispersive medium the higher frequencies are more penetrating, requiring greater ion-densities for reflection. Likewise the o wave-component is more penetrating than the x wave-component of the same frequency, and will reach a higher ion-density before reflection. The various levels of Figure 1 therefore are regions of ionization known, respectively, as the E-region at about 100 km, the F_1-region at about 180 to 200 km, and the F_2-region at about 250 to 400 km. The F_1- and F_2-regions exist separately only under small zenith-angles of the Sun, merging into a single F-region at large zenith-angles, or after sunset

The maximum ion-density of an ionized region can be calculated from (1) or (2) if the frequency at which one wave-component just penetrates the region is determined. This so-called "critical frequency" therefore represents the number of charged particles, N, in terms of equivalent numbers of electrons per cc, being a function of N. Under normal conditions, the maximum ion-densities for the E- and F_1-regions during the daytime change diurnally and seasonally as a function of the zenith-angle of the Sun, upon which may be superimposed a small change from year to year. Observations of these regions during solar eclipses have shown their ion-densities to decrease as a function of the concealed portion of the Sun's disc, without any appreciable lag in time. It is therefore generally concluded that the major and normal ionizing agent of the E- and F_1-regions during the daytime is ultra-violet light.

In view of these characteristics, the F_2-region appears to have an "anomalous" behavior. As first observed at Washington, the F_2-region was found to have a much lower maximal ion-density during the months of May to August, when the Sun was most nearly overhead, than during the months of October to March. Similarly, the diurnal characteristic does not exhibit the simplicity of the lower regions; in the temperate zones, the maximum ion-density usually occurs after noon and sometimes in the evening, while near the equator a double maximum is observed ordinarily, with a slight decrease near noon and the major maximum late in the afternoon. It has been shown, however, that in all locations the values at noon of maximum ion-density are proportional to values at other times during the hours of daylight, a high value at noon indicating a high average throughout the day.

A further study of this seemingly anomalous behavior has been possible with the establishment of observing equipment at the Huancayo Magnetic Observatory (Peru) in latitude 12° south and longitude 75° west, and at the Watheroo Magnetic Observatory (Western Australia) in latitude 30° south and longitude 116° west. Regular schedules of observations are maintained three times weekly. These observations, in conjunction with the published data from Washington by the Na-

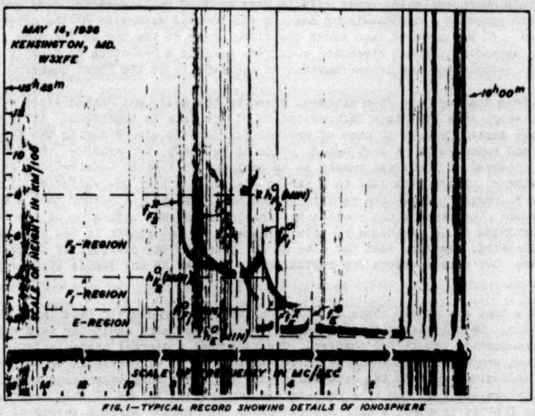
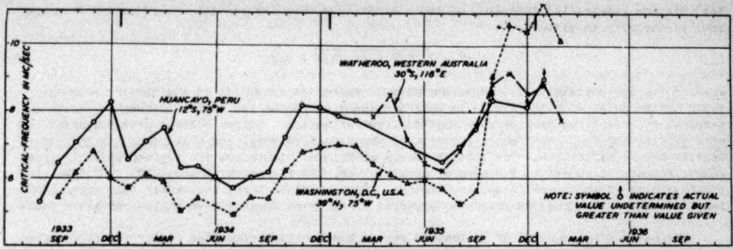


FIG. 1—TYPICAL RECORD SHOWING DETAILS OF IONOSPHERE



NOTE: SYMBOL ♁ INDICATES ACTUAL VALUE UNDETERMINED BUT GREATER THAN VALUE GIVEN

FIG. 2 —F_2 CRITICAL-FREQUENCY ("o" WAVE-COMPONENT), COMPARISON MONTHLY AVERAGES NOON VALUES, HUANCAYO, WATHEROO, AND WASHINGTON

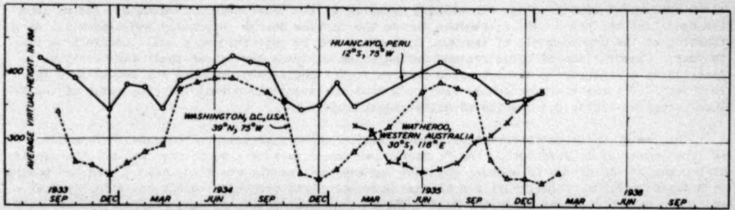


FIG. 3 —F_2-REGION, COMPARISON MONTHLY AVERAGES NOON VALUES MINIMUM VIRTUAL-HEIGHT, HUANCAYO, WATHEROO, AND WASHINGTON

tional Bureau of Standards, make more nearly possible a world-wide approach to the problem.

Monthly averages of values at noon of the critical frequency for the F_2-region are plotted for the three stations in Figure 2. The dotted curve for Washington shows the characteristic low values observed during the months of May to August as compared to the months of October to March. Likewise in Figure 3, the dotted curve shows the minimum virtual-height of the F_2-region at Washington plotted against the time of year. It is seen that the lowest critical frequencies and the greatest minimal virtual-heights are observed at Washington during the local summer. On the basis of this characteristic, these effects were assumed to be seasonal ones and some investigators have proposed a hypothesis of heating and thermal expansion of the upper atmosphere to explain them. It was assumed that under the direct rays of the Sun an increase in temperature and a corresponding thermal expansion occurred, causing a reduction in density of such magnitude as would account for the lesser maximum of ion-density in the local summer.

The data from Huancayo and from Watheroo given by the solid and dashed lines of Figures 2 and 3, respectively, show that this interpretation of the data is incorrect. It is observed that the average maximum values at noon of maximal ion-density occurs during the same months at both Watheroo and Huancayo as at Washington. Thus at Watheroo, for example, the maximal ion-densities are observed in the local summer as in contrast to similar observations at Washington during local winter. These data lead to a strong presumption that the variation of maximal ion-density of the F_2-region through the year is predominantly an annual rather than a seasonal effect. Furthermore, the data do not admit a hypothesis of thermal expansion of the form proposed, because the phenomena to be explained by this hypothesis do not appear in the Southern Hemisphere. It must be emphasized, however, that the data do not preclude the possibility of heating in the upper atmosphere, but merely remove the factual basis upon which the simple hypothesis was erected.

It is found that the annual means of F_2-region maximum ion-density show large variations from year to year. This leads to the impression that the ionizing agent for this region must experience corresponding functional changes. The fact that a diurnal characteristic exists shows the Sun to be the source of this ionizing force, whether it be ultra-violet or corpuscular in nature. This reasoning leads to the conclusion that the Earth must experience relatively large changes of solar radiation of the type responsible for the ionization of this region. While they are as yet limited to about a half sunspot-cycle, the annual maximum values of ion-density observed from year to year show a correspondence to sunspot-changes so far. The data, of course, are too restricted to reach any conclusion in this regard now. However, the possibility that values of F_2 critical-frequency may yield a sensitive measure of changes of solar radiation of this nature must be considered seriously. A day-to-day correspondence with observed sunspot phenomena is not to be expected necessarily when it is remembered that the sunspots in themselves may not be the source of the ionizing agent, but rather the manifestation of a more fundamental solar-variation which is otherwise invisible through the Earth's atmosphere. This is indicated from observed terrestrial-magnetic phenomena, the dependence of magnetic activity on sunspots being a statistical rather than a one-to-one correspondence.

It appears from the curves of Figure 3 that the minimum virtual-height of the F_2-region is a function of the zenith-angle of the Sun at all stations. In the case of Washington and Watheroo, a single annual wave appears in the graphs with the maximal virtual-heights when the Sun is most nearly overhead at each station, respectively, and decreasing as the noon zenith-angle increases. At Huancayo, a double wave is apparent probably due to the fact that twice each year the Sun is overhead, the noon zenith-angle increasing to a maximum in both the northern and southern skies. At Huancayo, two major departures from temperate-zone conditions are apparent, namely, the virtual height is a minimum at about the time that the Sun is overhead, increasing as the noon zenith-angle increases, and the change in virtual height is more nearly like the characteristic at Washington, 51° north of Huancayo, in approximately the same longitude, than the characteristic at Watheroo, which is only 18° farther south than Huancayo, although 169° farther west. Further, the average minimal virtual-height at Huancayo is higher for any month than at either Washington or at Watheroo.

The change of minimal virtual-height of the F_2-region appears to be of a seasonal nature, the character of the seasonal variation being reversed in the equatorial as compared to the temperate zones. However, this as yet cannot be considered as well established with data from only three stations. Until observations from other stations are available, it can be supposed also that the effect might be due to longitude-difference, however improbable such a hypothesis might seem. More westerly stations in San Francisco, Honolulu, or perhaps China or Japan, yielding similar data would be extremely valuable. In either case, it is interesting to speculate concerning the form of the virtual-height curve at locations where the transition from one type of variation to the other occurs. With regard to the changes of virtual height, a thermal hypothesis involving expansion and horizontal winds is not excluded, considering the forces imposed upon the motions of the ions in the Earth's magnetic field. Therefore, it does not seem impossible that a new hypothesis of thermal expansion may be devised to explain the reversal of character of the function of virtual height with zenith-angle from equatorial to temperate zones.

In considering the nature of the F_2-region, another factor, frequently overlooked, should be reconsidered. It was found during the solar eclipse of August 1932 that, in contrast with the effects observed in the lower regions, no decrease in the maximum ion-density which could be attributed to the eclipse was observed for the F_2-region. Subsequent observations during the eclipses of February 1934 and February 1935 indicated that a decrease actually took place, though less sharp than that for the lower regions. Because of the seeming conflict, the results during the later eclipses have been accepted as representative because of the better correspondence to preconceived theoretical ideas. However, one crucial point may have been overlooked. At the time of the eclipse of August 1932, the F_1- and F_2-regions were widely separated under the relatively small zenith-angle of the Sun. At the time of the February observations, the regions were nearly merged under the comparatively large zenith-angle. Under the latter condition, the maxima of the two regions are only slightly separated in height, so that the contribution of the upper F_1-region ionization to the maximum F_2-region ion-density must be large. Therefore, it is possible that the decrease of maximum F_2-region ion-density observed during the February eclipses may be attributed to the decrease in F_1-region ion-density, and not to a change in the primary ionizing agent of the F_2-region. This view makes the data during the various eclipse-observations mutually consistent, and leads to the conclusion that the primary ionizing agent of the F_2-region is not eclipsed at the time of the optical eclipse and, therefore, does not travel with the velocity of light.

This conclusion does not agree with the views of some other investigators who assume the primary ionizing agent in the F_2-region to be ultra-violet light. We believe, however, that at present the data show sufficient conflict in this regard as to leave unanswered the important question as to the ionizing agent of the F_2-region until accumulation of further data.

While the view advanced here cannot be considered as established on the basis of a single set of eclipse-measurements during the eclipse of August 1932, it is capable of experimental verification. Further eclipse-observations in locations where the separation of the two regions is great must be conducted. Furthermore, a study of the comparative maximum ion-densities of the F_2-region in the Northern and Southern hemispheres should give information as to the contribution of the F_1-region ionization to the maximum F_2-region ion-density. During the months when the maximum F_2-region ion-densities are the greatest, the separation of the F_1- and F_2-regions is very slight at Washington, but very marked at Watheroo. Likewise near the opposite solstice when the maximum ion-density is a minimum, the two regions are nearly merged at Watheroo, but widely separated at Washington. Therefore, according to the view proposed above, it might be expected that there would be at Washington a lower local midsummer and a higher local midwinter value of maximal ion-density than for corresponding local seasons at Watheroo. Further information may be expected with the extension of the observational series.

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ON THE EFFECTIVE GROUP-VELOCITIES OF LOW-FREQUENCY RADIO TIME-SIGNALS AND THE APPARENT VARIABILITY OF VELOCITY WITH THE REGION OF THE EARTH TRAVERSED

H. T. Stetson

This paper is being printed in full in the September 1936 issue of the Journal of Terrestrial Magnetism and Atmospheric Electricity.

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POTENTIAL DISTRIBUTION ABOUT A LEAKY CYLINDER

Louis B. Slichter

(Abstract)

The electrical potentials due to a point-source electrode located on the axis of an infinite circular cylinder embedded in a space of different conductivity were evaluated with the aid of the Massachusetts Institute of Technology's differential analyzer. An application of the results to some field-data from geophysical prospecting was illustrated. In this example the measurements of potentials in two neighboring drill-holes were used to obtain an estimate of the order of magnitude of the cross-section of an ore-vein between the two holes.

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ACTUAL AND POTENTIAL RESULTS FROM ELECTRICAL EXPLORATION OF THE ATMOSPHERE

O. H. Gish

Interesting information about the atmosphere has been provided by several types of electric measurements, some made at the surface of the Earth, others made in the free atmosphere with the aid of kites, balloons, or other aircraft. Franklin with his kite made the first electrical exploration of the atmosphere. The scientific and practical results are well known, at least they have become commonplace, perhaps so much so that their significance for human thought and affairs is not adequately appreciated. It was in 1750 in a letter to Collinson, member of the Royal Society of London, that he announced the first experimental evidence that electricity is generated in the air during storms.

In the same letter, among other applications of the information gained from his exploration, he indicated a method of protecting buildings from lightning. The trail which was blazed by this pioneer work of Franklin is a long one, which has been traversed and extended by many illustrious physicists since his time. It is that trail which we shall chiefly follow here.

Before proceeding upon that course, however, some of the more important classes of electric or electromagnetic methods of exploring the atmosphere will be mentioned. The measurements of the variations, of daily period, in the Earth's magnetic field and of the associated electric phenomena, earth-currents, may be considered one of these. It has long been surmised that the origin of these electromagnetic phenomena is outside the Earth, and Balfour-Stewart in 1882 suggested an explanation of them which implied a relatively high degree of conductivity of the high atmosphere and also required that the air at those levels undergoes certain systematic movements. Balfour-Stewart's conception has been developed in quantitative form and tested by Schuster, Chapman, and others. Here is an indirect means of obtaining information regarding the high atmosphere--information which supplements that obtained by other methods.

Another class of methods is that used for investigating the cosmic radiation. The development of these methods and the "discovery" of cosmic radiation have progressed by so many steps, taken by so many different investigators, that it is difficult to assign a date of discovery and is well nigh impossible to assign credit for the discovery to any one individual. However, development can be traced from near the beginning of the present century. That information regarding cosmic radiation may be used in conjunction with other data for inferring other features of the atmosphere will be illustrated by a specific case later. The so-called "barometer-effect" in cosmic radiation, a decrease of intensity at the Earth's surface when the barometric pressure increases, varies in an unexplained manner, which, however, may depend upon the distribution of air-mass in a region of several kilometers about the point where the observations are made. This feature may therefore have potential interest to the meteorologist.

Observations on the transmission of radio waves in the atmosphere are another source of information regarding certain conditions in the high atmosphere. These have already verified and made more precise the inference of Balfour-Stewart, namely, that portions of the high atmosphere are highly ionized. The position of these regions is determined and other important results are being obtained by this means of exploring the atmosphere. Its possibilities are apparently great, but further discussion cannot be devoted to it here.

Various measurements, made at the surface of the Earth, of the electric field and other factors which define the electric state and processes in the atmosphere, depend to a marked extent upon the dynamic processes and also upon some minor constituents of the atmosphere. This is especially evident in so far as concerns the lower part of the troposphere, but it is surmised that a somewhat similar, although less conspicuous, dependence upon the meteorology of the higher atmosphere also exists--particularly during electrical storms. These measurements constitute a branch of electric exploration which has been given chief attention for the periods of fair weather. Exploration during storms has been somewhat neglected. Neither of these aspects of electrical measurements, or of others which reveal features of the atmosphere, will be given further consideration at this time, but we shall turn now to measurements made chiefly from balloons.

Franklin's letters to Collinson, translated into French by Dalibard, were published in 1751 and thus his results and interpretations soon came to the attention of the scientists of the time. They were enthusiastically received by some but others regarded them with open disdain.

De Romas in 1752 made bolder experiments with kites. In Franklin's experiments relatively weak sparks were obtained, but Chauveau (B. Chauveau, Electricité Atmosphérique, Paris, 1922, contains an excellent historical review; quotation is translation of end of section 4, p. 7) reports that de Romas obtained "manifestations truly comparable in intensity with those of lightning." Although these experiments started an epoch in the study of atmospheric electricity, yet they appear to have been the last in which kites were used until nearly a century later.

During the latter part of the eighteenth century, balloons capable of carrying men were developed, and in the year 1804 the first balloon-flight devoted to scientific observations was made by Gay-Lussac and Biot. These renowned scientists made measurements of the electric field in the air following a method outlined, for use in balloons, by the Swiss physicist de Saussure in a memoir published 20 years earlier.

Then there followed a long period of inactivity as regards systematic measurements pertaining to atmospheric electricity. Although, in 1840, Peltier at Paris and, in 1888, L. Weber at Breslau used kites and captive-balloons for holding a wire aloft on which to collect electricity from the air, yet since such a method is not capable of giving a quantitative measure of the distribution of the electric field with altitude these experiments did little to advance knowledge of the electrical state of the free atmosphere.

The electric field-strength up to an altitude of one km was measured on a free-balloon flight made by Lecher from Vienna in 1886 under the direction of F. Exner (Wien. Ber., v. 93, p. 288, 1886). From these measurements it was concluded that the field-strength, or potential gradient, increased with altitude, which was in accord with the theory which Exner entertained at that time. J. Tuma (Wien. Ber., v. 101, 2a, p. 1556, 1892) in 1892 made a successful flight from Vienna, and obtained a considerable number of measurements of potential gradient at about 2-km altitude.

These, too, were considered to indicate an increase with altitude, although less in amount than found by Lecher. Later observations made principally in manned balloons, however, all show that the potential gradient tends to decrease with altitude.

Up to the time of the World War numerous balloon-flights had been made for the purpose of measuring one or more of the elements which pertain to the electrical state of the atmosphere. The altitudes reached in these flights seldom exceeded six km above sea-level, although in a few flights made by Wigand and associates an altitude of nearly nine km was reached. The reports of results obtained on these flights constitute the main body of available information about the electric state of the troposphere except in so far as such information may be obtained from measurements made at the Earth's surface. They are listed in approximately chronological order in Table 1.

Table 1--Balloon-flights on which measurements pertaining to electric state of the atmosphere were made

Author	Starting point	No. of flights	Reference to publications
			Manned balloons
Le Cadet	Meudon, France (near Paris)	2	Ann. Univ. Lyon, fasc. 35, 1898; Ch. André, Report of Le Cadet's results, C.-R. Acad. Sci., v. 117, p.. 729, 1893
R. Börnstein	Berlin	2	Zs. Luftschiffahrt, May 1894, and general account in Verh. Phys. Ges., Berlin, v. 13, pp. 35-50, 1894
O. Baschin	Berlin	1	Zs. Luftschiffahrt, March-April 1894
J. Tuma	Vienna	7	Wien, SitzBer, Ak. Wiss., v. 108, p. 227, 1899
H. Ebert	Munich	3	München, SitzBer, Ak. Wiss., v. 30, pp. 511-532, 1900; v. 31, p. 35, 1901; Beitr. Geophysik, v. 6, p. 66, 1903; Terr. Mag., v. 6, pp. 97-118, 1901
G. Lüdeling	Berlin	2	Ill. aeron. Mitt., v. 7, pp. 321-329, 1903
F. Linke	Berlin Göttingen	10 2	Göttingen, Abh. Ges. Wiss., v. 3, pp. 1-90, 1903; Diss., Berlin, 1901; Ann. Physik., v. 7, p. 231, 1902; Physik. Zs., v. 4, p. 661, 1903
H. Gerdien	Berlin (Charlottenburg)	7	Göttingen, Nachr. Ges. Wiss., pp. 382-399, 1903; pp. 277-299, 1904; pp. 447-458, 1905
A. Wigand and associates	Mostly from Bitterfeld, Germany	19	Ann. Physik., v. 59, pp. 689-742, 1919; v. 66, pp. 81-109, 1921; Physik. Zs., v. 22, pp. 36-46, 1921
			Sounding balloons
P. Idrac	Trappes, France	44	Mém. Office Nation. Mét., Paris, No. 18, 1928

These results show that the air-conductivity generally increases with altitude in a fairly regular manner. The departures from that trend seem to consist of a decrease in regions where such meteorological features as haze-layers, clouds, or even temperature-inversions were observed. The ionic density also increases somewhat with altitude, but the observed average increase, according to Gerdien and Wigand, is somewhat less than would be expected from the measured conductivity, provided the mobility varies inversely as the pressure. Errors in measurements of ionic content, arising from the presence of large and intermediate ions, may have led to this result. Thus the measured value of ionic content was doubtless too large owing to the collection of some larger ion-species which, however, do not contribute appreciably to the conductivity. At higher levels the larger ions are doubtless not so abundant as at lower levels; hence, the ion-count there is not increased so much by that cause.

Although the observed values of potential gradient often did not vary systematically with altitude, especially at altitudes below one or two km, yet on the average, at higher levels, it decreased nearly exponentially, approaching a value of about five volts per meter at ten km above sea-level. Only a few of the flights with manned balloons approached this height. The sounding balloons used by Idrac, however, frequently went higher. A few ascended to 15 km or more and one reached an altitude of 20 km. The results obtained with the sounding balloons are, however, very irregular even at the higher levels, and, although the mean values of the potential gradient tend to decrease with altitude, yet even these mean values are far from those indicated by previous measurements. If the features indicated by these sounding-balloon measurements are verified by future investigations, then the present view regarding the factors which determine the electrical state of the atmosphere will have to undergo radical changes. However, one is inclined to accept the results obtained on the manned balloons until the results of Idrac's pioneer endeavor have been verified.

The use of sounding balloons for obtaining autographic records of air-conductivity as well as of potential gradient should be feasible and would seem to offer advantages over manned balloons. If, as seems likely, some features of the instrumentation which has been developed for radio-meteorographs can be adapted to measurements of potential gradient and air-conductivity, then with sounding balloons valuable information about some electric features of the air in storm-areas may be obtained.

If the air-conductivity increases and the potential gradient decreases with altitude, as is indicated by all modern upper-air data except those of Idrac, then the vertical conduction-current, which is the product of conductivity and gradient, should vary less than either of those factors.

In order to test this more precisely, Gerdien, and later Wigand, made both air-conductivity and potential-gradient measurements during each of several flights. Wigand concluded from his observations, which extended over a considerably greater range of altitudes than those of Gerdien, that the vertical conduction-current decreases somewhat with altitude.

If this conclusion should be supported by future observations and should be shown to be general, then one would be forced to conclude that the flow of electricity through the atmosphere contains a component which is of the character of a convection-current and that that component increases with altitude.

At relatively low levels, perhaps only in the first few meters above the Earth's surface, one might expect to find such a component, which would result from a combination of the so-called electrode-effect and the mixing action that takes place due to turbulence of the air.

The first measurements of the electrical conductivity in the stratosphere were made on the National Geographic Society - Army Air Corps stratosphere flight of the Explorer II. Satisfactory registration of the conductivity was obtained throughout the flight with apparatus designed and constructed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. This flight started from a point 15 miles (24 km) southwest of Rapid City, South Dakota, at about 7^h, 105th west meridian time, and ended about eight hours later at a point some 235 miles (380 km) away and in a direction 10° south of east from the starting point.

The record obtained shows that the air-conductivity in general increased with altitude (see Fig. 1 in author's paper before the Section of Meteorology printed in these Transactions); the highest value, which was recorded at 18-km (60,000-ft) altitude, was about 100 times the average value observed on the Carnegie at the surface over the oceans. The values recorded on the ascent were generally less than those found on the descent probably because dust or other "polluting" substances given off by the balloon affected the "sample" of air on the ascent but not on the descent because, when ascending, the gondola was running into air which had been adjacent to the balloon, whereas it was running away from it on the descent.

Positive-ion conductivity was always less than that for negative ions, except for one spurious negative-conductivity group at the "top," and, contrary to expectation, the negative conductivity at the high levels, or low pressures, did not increase relative to the positive conductivity at corresponding level. This leads one either to question whether the rapid increase of negative mobility reported from experiments in the laboratory at low pressures occurs for the type and intensity of ionization which prevail in the high atmosphere, or else to conclude that this is an indication that more water-vapor may exist in the high atmosphere than is generally expected. The latter alternative rests on the claim that the abnormal increase of negative mobility is less marked when small quantities of water-vapor are present. This observed feature is, in case of the first alternative, important for considerations of some radio phenomena and, in case the second alternative holds, then the information is of interest to the meteorologist.

An estimate of the potential difference between the Earth and the high atmosphere, based on the conductivity-data and on measurements of air-earth current made at the Earth's surface, indicates that the high atmosphere is at about 400,000 volts higher potential than the Earth. Nearly half of this increase occurs in the lower two km. This estimate is in satisfactory accord with that derived from all direct observations of the potential gradient in the free atmosphere except those of Idrac.

Throughout most of the region where the conductivity was measured the cosmic radiation is doubtless the predominant ionizing agent; hence, it is of interest to compare the observed conductivity with that calculated from the observed cosmic-radiation intensities. The values of conductivity calculated from Regener's cosmic-ray data (E. Regener and G. Pfotzer, Physik. Zs., v. 35, pp. 779-784, 1934), using generally accepted relations, were all greater than corresponding observed values. This statement holds for positive as well as negative conductivity. The ratio of the calculated values to those observed on the descent increases regularly in the region from altitudes of 6 to 18 km. This, together with other circumstances, led to the surmise that the recombination-coefficient for small ions varies, not as the first power of the pressure, but more nearly as the one-half power. With such an adjustment the calculated and observed values are in excellent agreement throughout the 12 km of altitude from 6 to 18 km. A more complete report on apparatus, results, and interpretations is being prepared for publication in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

Lack of agreement in the lower atmosphere was expected, chiefly because of the presence there of condensation-nuclei. The distribution of these is derived from the difference between calculated and observed conductivity (see Fig. 2 of the author's paper before the Section of Meteorology printed in these Transactions). If the data for altitudes from 18 to 22 km are interpreted in a similar manner, a surprising conclusion is reached, namely, that the air in this high stratum contained several thousand nuclei per cubic centimeter. However, from the fact that mother-of-pearl clouds have been frequently observed at this level, one may infer that nuclei are not uncommon at such levels.

The inferences which are drawn from the electric measurements made in the free atmosphere must be recognized as simply inferences, some having a fairly substantial foundation in observed facts, others being little more than ideas suggested by the facts. The former lie on the border of actual results. The latter are designed more particularly to illustrate some of the potential results which may be obtained by this type of electrical exploration of the atmosphere.

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MAGNETIC SURVEY IN THE LEHIGH VALLEY

Maurice Ewing and H. H. Pentz

A large magnetic anomaly was found in the northern half of the Allentown Quadrangle. Its center is at latitude 40° 41' and longitude 75° 23'. It is roughly circular in shape and about eight miles in diameter. The maximum variation is about 1000 gammas (1 gamma = 0.00001 C.G.S. unit) for the vertical component and 750 gammas for the horizontal.

General geology

The magnetic anomaly lies in the Kittatinny or Great Valley of the Appalachian Province. The basement-rocks of the region consist of pre-Cambrian metamorphic rocks of igneous and sedimentary origin. Two small outcrops of the basement-rocks occur within the survey. The larger of these is described by B. L. Miller [see 1 of "References" at end of paper] as "two small hills--Quaker Hill and Pine Top, about 2 1/2 miles north of Bethlehem--that belong geologically to the Appalachian Mountains. They owe their present elevation to a pronounced fault that bounds the hills on the north." The outcrops follow the structural trend of the region and the second outcrop is at the eastern end of the survey. Concentrations of magnetite occur in the exposed basement-rocks in the southern part of the quadrangle.

Overlying the basement-rocks are dolomitic limestones of Cambrian and Ordovician age. Most of the stations of the survey lie on this limestone and very little information is available about the depth to the basement-rocks. Limonite ores are distributed irregularly through the limestone. According to Miller [1] there is "one belt of iron mines that extends in an east-by-north direction through Shoenersville and Hanoverville to Hollo. Many other mines of the limestone regions, however, are not included in these belts." It is commonly accepted that the limonite ores are residual, and probably superficial in nature.

A few stations in the northwest part of the survey lie on the Martinsburg shale of Ordovician age. The shale lies above the limestone as shown on the map in Figure 1.

The Hardyston Quartzite and the cement-limestone are thin horizons which are not considered significant in the present survey.

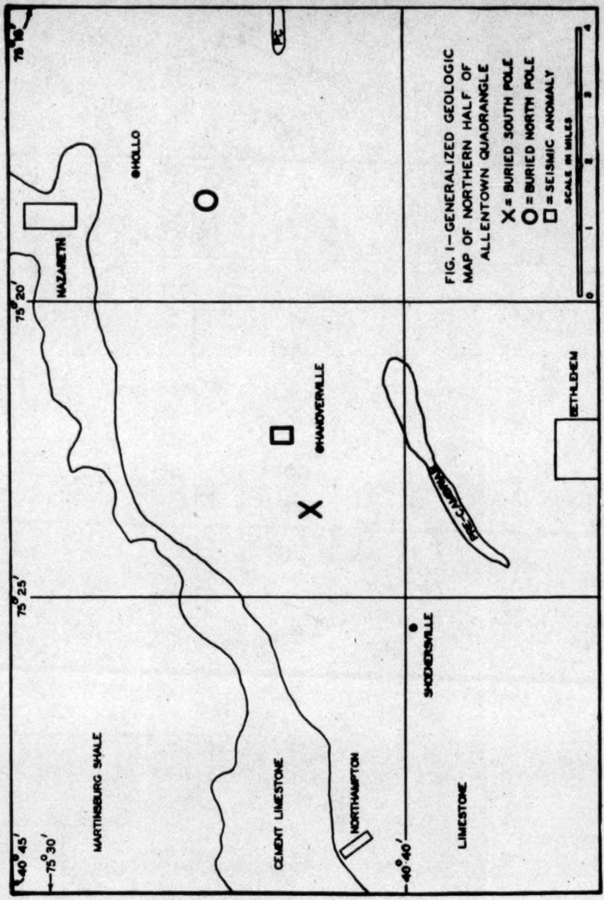

FIG. 1—GENERALIZED GEOLOGIC MAP OF NORTHERN HALF OF ALLENTOWN QUADRANGLE

X = BURIED SOUTH POLE
O = BURIED NORTH POLE
□ = SEISMIC ANOMALY
SCALE IN MILES
0
1
2
3
4
40°45'
75°30'
75°25'
75°20'
75°15'
40°40'
MARTINSBURG SHALE
CEMENT LIMESTONE
LIMESTONE
NORTHAMPTON
SHOENERSVILLE
HANOVERVILLE
NAZARETH
HOLLO
BETHLEHEM
PRE-CAMBRIAN
PC

Magnetic observations

An Askania magnetic vertical-field balance, adjusted to a sensitivity of 34.8 gammas per scale-division, was used to measure the anomalies in the vertical component of the magnetic field of the Earth. This instrument did not have a temperature-compensated system, but each reading was corrected for temperature-changes. An Askania horizontal-field balance, adjusted to a sensitivity of 19.7 gammas per scale-division, was used for the horizontal component. This instrument had a temperature-compensated system and no appreciable corrections for temperature-changes were necessary.

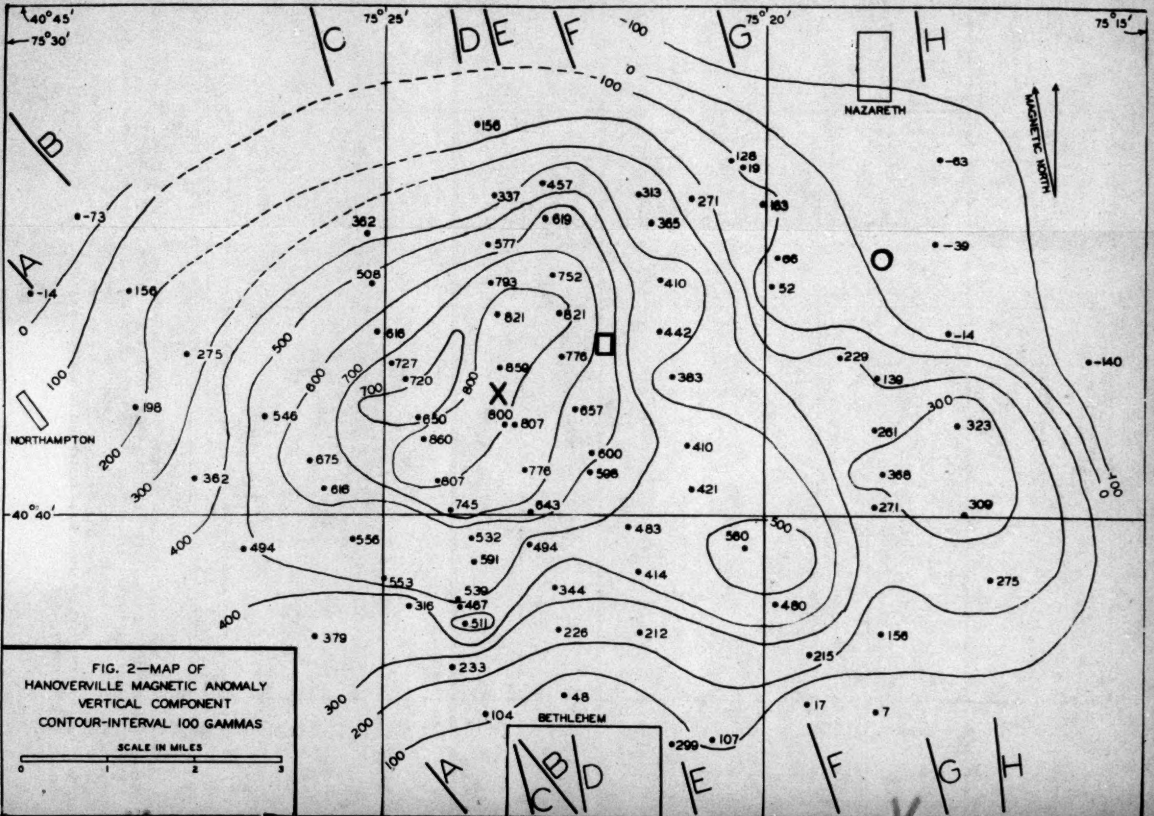
40°45'
75°30'
75°25'
75°20'
75°15'
40°40'
A
B
C
D
E
F
G
H
NAZARETH
NORTHAMPTON
BETHLEHEM
MAGNETIC NORTH
O
X
-100
0
100
200
300
400
500
600
700
800
-73
-14
156
275
198
362
494
379
233
104
48
299
107
17
7
156
215
480
275
309
323
261
368
271
580
414
483
421
410
383
442
410
52
66
183
128
19
271
313
365
-63
-39
-14
-140
229
139
156
457
337
619
577
362
508
616
727
720
650
860
675
616
546
793
752
821
821
776
859
807
657
600
598
776
807
745
643
532
494
591
556
553
539
467
511
316
344
226
212
SCALE IN MILES
0
1
2
3

FIG. 2—MAP OF
HANOVERVILLE MAGNETIC ANOMALY
VERTICAL COMPONENT
CONTOUR-INTERVAL 100 GAMMAS

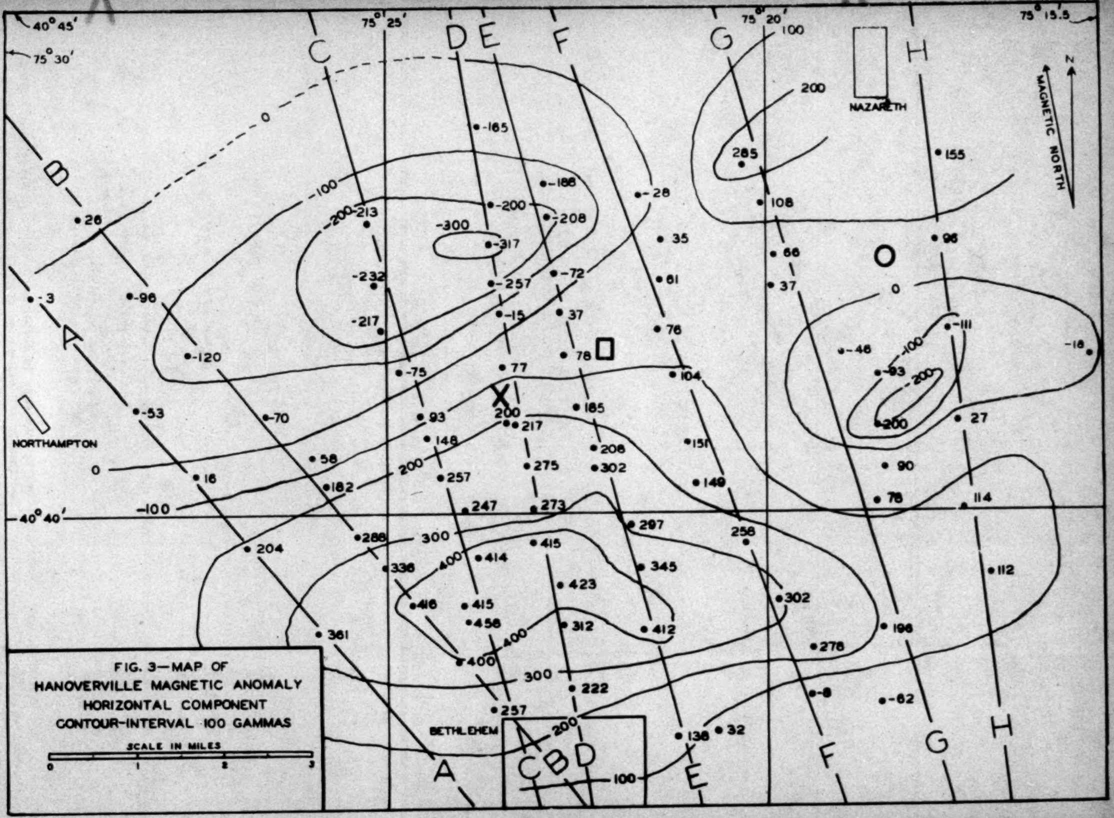
40° 45'
75° 30'
75° 25'
75° 20'
75° 15.5'
40° 40'
N
MAGNETIC NORTH
NAZARETH
NORTHAMPTON
BETHLEHEM
A
B
C
D
E
F
G
H
O
X
0
-100
-200
-300
100
200
300
400
26
-3
-96
-120
-53
-70
16
58
182
204
288
336
361
-213
-232
-217
-75
93
148
257
247
-165
-188
-200
-208
-317
-257
-72
-15
37
77
78
217
185
208
275
302
273
297
414
415
416
458
423
312
412
400
222
-28
35
61
76
104
151
149
258
345
302
278
138
32
-8
285
108
66
37
155
96
-46
-93
-111
27
90
76
114
112
196
-62
-18

FIG. 3—MAP OF
HANOVERVILLE MAGNETIC ANOMALY
HORIZONTAL COMPONENT
CONTOUR-INTERVAL 100 GAMMAS

SCALE IN MILES
0
1
2
3

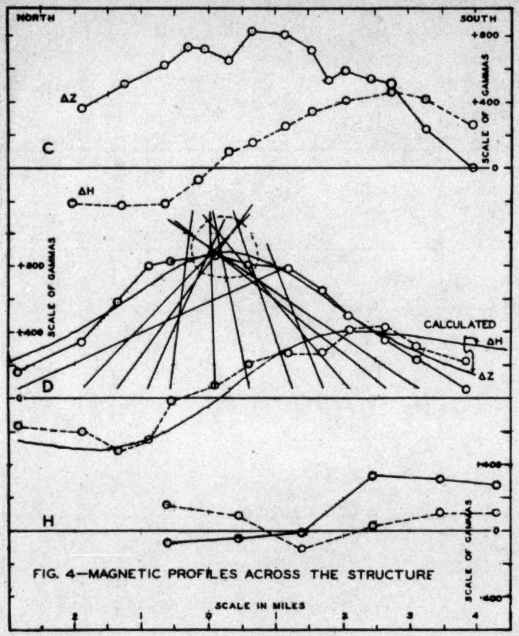

FIG. 4—MAGNETIC PROFILES ACROSS THE STRUCTURE

Absolute values for the components of the magnetic field were not determined, all readings being relative to a base-station, which was selected near the center of the survey. The values taken as "normal" for purposes of calculating actual values of the anomalies were selected after inspection of the collected data. Corrections for diurnal changes and other fluctuations were obtained by returning the instruments to base-station for check-readings at three- or four-hour intervals. The instruments used were obtained as a loan from the Department of Geology of Princeton University.

Results

Figure 2 shows the variations in vertical intensity which were observed. It is seen that at the center of the survey, which is marked by a cross on the maps, there is a maximum of vertical intensity of about 1000 gammas above normal. The iso-anomaly lines are approximately circular and indicate that the intensity gradually decreases to normal at a distance of more than four miles from the center. This is the pattern which would be given by south-seeking magnetic pole, buried deeply beneath the center of the survey.

Figure 3 shows the variations in horizontal intensity which were observed. It is seen that there is a maximum of intensity at a point about two miles south (magnetic) of the center and a minimum of intensity at a point at the same distance north of it. The iso-anomaly lines indicate this situation clearly, and their pattern again is that which would be given by a south-seeking pole deeply buried beneath the point, near the center of the survey, which is marked by the cross.

The pattern of the iso-anomaly lines in both maps is distorted somewhat from the simple form described above. This distortion is confined to the eastern portion of the survey and is exactly what would be produced by a north-seeking pole, located at the point marked with a large circle, nearer the surface and weaker in strength than the south-seeking pole which produces the principal features of the anomaly.

The possibility that this entire magnetic anomaly is produced by the limonite-deposit mentioned in the first section of this report should be considered. There are three strong reasons against this interpretation. (1) Magnitude--Following Reich [2] in taking the susceptibility of limonite as 200×10^{-6}, assuming (a) the magnetization of the limonite produced solely by induction of the Earth's field and (b) the entire region of the survey to be composed of pure limonite, one obtains a maximum vertical anomaly less than one-tenth of the observed value. (2) Shape--It would require a very specialized distribution of limonite near the surface to produce curves characteristic of a concentrated buried pole; the probability of such a distribution is low. (3) Polarity--A residual deposit of limonite would be magnetized with a south-seeking pole uppermost; the pole marked on the map by a circle is a north-seeking pole.

It is highly probably that the observed effects are produced by two strong poles located in the basement-rocks. In Figure 4 three sections across the anomaly are shown. On section D an estimate of the depth to the pole has been made by combining vectorially the two components of the anomalies at each station. It is seen that the vectors obtained intersect reasonably well in a region, enclosed by a dotted line, about 2.3 miles beneath the surface. Application of any one of the current "rules" for estimating depth [3] from the distance between extreme values of the horizontal anomaly, etc., yields depths of the same order of magnitude.

On section D of Figure 4 are shown curves for the anomalies which would be produced by a concentrated south pole of strength 7.5×10^{13} C.G.S. unit at a depth of 2.8 miles. The agreement between theoretical and observed curves is fairly satisfactory.

The elongation of the iso-anomaly contours, for the horizontal component, in the east-west direction may be interpreted to mean that the buried south pole is elongated in this direction.

There is no strong magnetic indication of the outcrop of basement-rocks at Quaker Hill, which shows that at this point the magnetic content is very low. Professor B. L. Miller (verbal communication) has stated that this outcrop represents an acid-phase of the basement-complex. It is clear that there is wide variation in the magnetic content of the basement-rocks in this region, and that it is impossible to make a general survey of the basement-topography by the magnetic method. It is likely, however, that magnetic studies will supplement geological methods in differentiating the various phases of the basement-complex.

An anomaly which was detected by seismic measurements in this region has already been described [4,5]. Its location is marked by a square on the maps. From the seismic evidence it was concluded that a zone of faulted or shattered limestone at least a thousand feet in width, probably extending east by north, was present. It seems possible that these anomalies are related.

The occurrence of "cement-limestone" in the quarry of the National Cement Company, just east of the square on the maps, at a point far removed from the main belt of cement-limestone, indicates a pronounced fault.

Conclusions

(1) The large magnetic anomaly is probably due to a concentration of magnetite in the basement-rocks at a depth of the order of two miles.

(2) The outcrop of the basement-rocks at Quaker Hill is but slightly magnetic.

(3) The line joining the two buried magnetic poles passes through the point where an anomaly had been detected by seismic measurements.

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[1] B. L. Miller, Topographic and geologic atlas of Pennsylvania, No. 206, Allentown Quadrangle, p. 18.
[2] H. Reich, Angewandte Geophysik für Bergleute und Geologen, Part I, p. 53.
[3] C. A. Heiland, Discussion, Trans. A.I.M.E., v. 97, p. 212, 1932.
[4] M. Ewing and A. P. Crary, Trans. Amer. Geophys. Union, 16th annual meeting, p. 100, 1935.
[5] M. Ewing, Penn. Acad. Sci., 1936.

Lehigh University,
Bethlehem, Pennsylvania

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AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

SECTION OF OCEANOGRAPHY

Washington, D. C.
April 30, 1936

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THE OCEANOGRAPHIC ACTIVITIES OF THE HYDROGRAPHIC OFFICE AND THE UNITED STATES NAVY DURING APRIL 1935 TO APRIL 1936

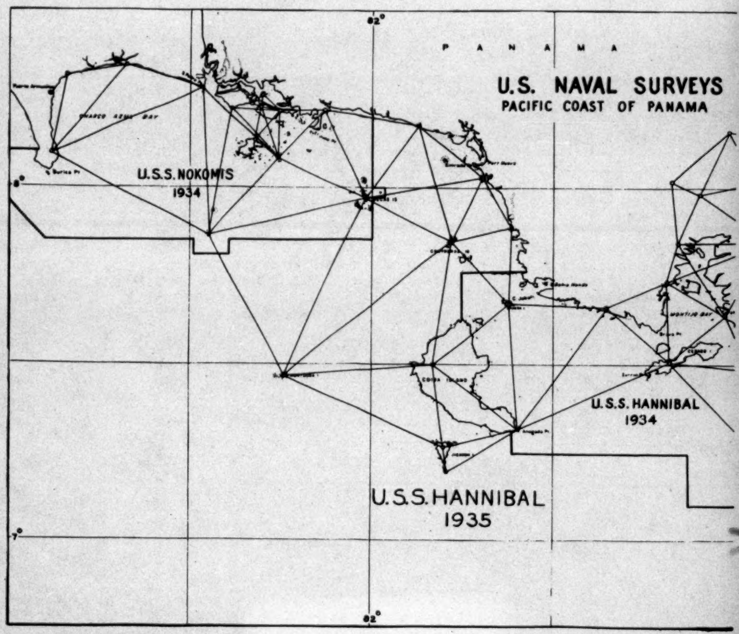
L. R. Leahy

As in previous years, most of the oceanographic work of the Hydrographic Office and the United States Navy related to the following various fields of activities, and was conducted in oceanic areas widely separated.

United States Naval surveys--The Hydrographic Office program of accurately surveying and charting Caribbean and Central American waters continued during the past year with gratifying results.

The U.S.S. Hannibal completed the survey of the waters of the south coast of Panama, bringing to a close the extensive undertaking started in 1929 of accurately charting the entire Pacific Coast of the Republic of Panama (Fig. 1). During this period, a rigid geodetic net, of an accuracy of better than second order, has been developed and joined to eight astronomical observation-spots. Aerial photo-mapping has played an important part in the execution of this project, not only in the development of the coast-line and adjacent topography, but also in the reconnaissance incidental to the surveys. The value and additional safety that mariners in general are receiving, and will continue to receive, from the resulting charts, more than justify the efforts made by the Hydrographic Office in conducting surveys of such important waters.

The U.S.S. Hannibal also completed, during the season of 1935, the survey of the Gulf of Nicoya, Costa Rica. This area also demanded accurate charting due to its increasing importance and the incompleteness and inaccuracy of existing charts.



In collaboration with the Government of Colombia, the U.S.S. Nokomis completed a survey of the Bay of Cartagena and its approaches. In addition, the Nokomis conducted hydrographic surveying operations in the approaches to the Rio Magdalena, including a detailed development of Puerto Colombia.

The U.S.S. Oglala and auxiliaries conducted surveys among some of the Aleutian Islands.

Charts from United States Naval surveys--Six new Hydrographic Office charts, based upon original United States Naval surveys, were published during the calendar year 1935.

Echo (sonic) soundings obtained by United States Naval vessels--A tabulated list of echo (sonic) soundings taken by United States Naval vessels from January 1, 1935 to December 31, 1935, is as follows:

U.S.S. Tuscaloosa - 90 sonic soundings in North and South Atlantic, crossing 3° N in 45° 55' W, 0° 08' S in 30° 00' W, and 4° 50' S in 35° 00' W.

U.S.S. Hannibal - 240 sonic soundings in North Atlantic en route to Panama Canal, crossing 34° 55!5 N in 74° 45!5 W, 20° 25' N in 74° 05' W, and 9° 39' N in 79° 48' W.

U.S.S. Augusta - 140 sonic soundings en route to Australia and East Indian waters, crossing 24° 16' S in 112° 12' E, 6° 59' S in 156° 17' E, 15° 05' S in 105° 05' E, and 38° 30' S in 140° 15' E.

U.S.S. Nokomis - 55 sonic soundings in North Atlantic en route to Panama Canal, crossing 35° 21' 15" N in 74° 14' 25" W, 19° 55' 00" N in 74° 25' 00" W, and 9° 24' 12" N in 79° 54' 43" W.

U.S.S. Ramapo - 1414 sonic soundings in North Pacific en route San Pedro, California, to Manila, Philippine Islands, crossing 34° 08' N in 122° 35' W, 25° 28' N in 175° 20' E, and 12° 50' 30" N in 124° 42' E.

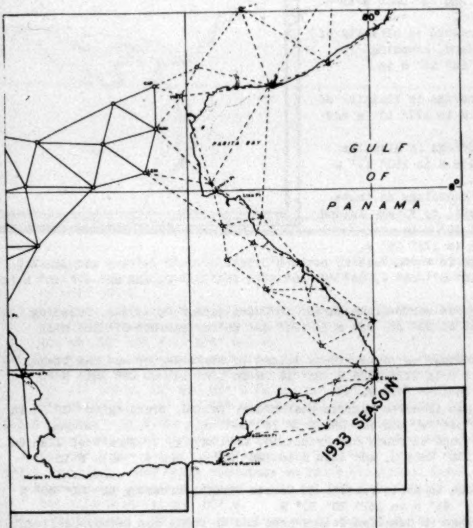


FIG. I

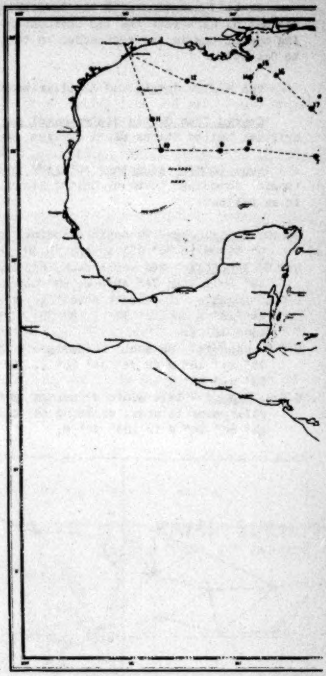
U.S.S. Hannibal - 38 sonic soundings en route Balboa, Canal Zone, to Gulf of Nicoya, Costa Rica, crossing 7° 52' 30" N in 83° 00' W, and 9° 20' 05" N in 84° 34' 20" W.

U.S.S. Ramapo - 1146 sonic soundings en route Manila, Philippine Islands, to San Diego, California, crossing 18° 48' N in 122° 28' 30" E, 32° 06' N in 172° 28' W, and 33° 51' N in 120° 54' 00" W.

U.S.S. Hannibal - 60 sonic soundings en route Gulf of Nicoya, Costa Rica, to Balboa, Canal Zone, crossing 9° 23' 30" N in 84° 41' 20" W, 7° 42' 30" N in 82° 54' 00" W, and 8° 38' 40" N in 84° 00' 45" W.

U.S.S. Hannibal - 45 sonic soundings while making passage Gulf of Nicoya, Costa Rica, to Balboa, Canal Zone, crossing 9° 18' 25" N in 84° 28' 15" W and 8° 27' 30" N in 83° 46' 00" W.

U.S.S. Nokomis - 25 sonic soundings in the Caribbean Sea, crossing 9° 41' 20" N in 79° 33' 30" W, and 10° 23' 13" N in 75° 32' 14" W.



U.S.S. Bushnell - 343 sonic soundings en route San Diego, California, to Pearl Harbor, Territory Hawaii, crossing 32° 19' N in 119° 26' W, 30° 54' 40" N in 127° 16' W, and 21° 06' 30" N in 157° 48' 15" W.

U.S.S. Nautilus - 20 sonic soundings near Gardner Pinnacles, crossing 25° 35' 00" N in 167° 57' 00" W and 25° 40' 00" N in 167° 42' 00" W.

U.S.S. Farragut - 40 sonic soundings in Aleutian Island Area, crossing 53° 30' 30" N in 169° 03' 00" W and 52° 16' 30" N in 175° 54' W.

U.S.S. Dewey - 55 sonic soundings in Aleutian Island Area, crossing 54° 21!3 N in 165° 33!3 W and 53° 32!5 N in 165° 54!5 W.

U.S.S. Indianapolis - 50 sonic soundings in Aleutian Island Area, crossing 54° 19' N in 158° 25!4 W and 54° 07' N in 166° 14!8 W.

U.S.S. Raleigh - 80 sonic soundings in Aleutian Island Area, crossing 54° 23' N in 158° 42' W and 51° 39!6 N in 175° 39!5 W.

U.S.S. Pennsylvania - 72 sonic soundings en route Midway Island to Pearl Harbor, Territory Hawaii, crossing 27° 45!8 N in 177° 20' W, 25° 21!5 N in 168° 08!4 W, and 21° 24' N in 157° 59' W.

U.S.S. Ramapo - 619 sonic soundings in North Pacific en route San Diego, California, to Pearl Harbor, Territory Hawaii, crossing 32° 17!5 N in 118° 49' W, 30° 14' N in 137° 21' W, and 28° 08!5 N in 177° 08' W.

U.S.S. Louisville - 90 sonic soundings in vicinity of Unimak Pass and Unalaska Island, crossing 54° 20' N in 166° 45' W and 53° 25' N in 166° 10' W.

U.S.S. Louisville - 45 sonic soundings in vicinity of Midway Island, crossing 28° N in 177° 10' W and 28° N in 176° 50' W.

U.S.S. Tuscaloosa - 10 sonic soundings in Aleutian Island Area, crossing 54° 11!5 N in 166° 11' W and 54° 10' N in 166° 22!2 W.

U.S.S. West Virginia - 145 sonic soundings en route Pearl Harbor, Territory Hawaii, to Midway Island and return, crossing 21° 52' 10" N in 161° 43' 30" W and 27° 50' N in 177° 26' W.

U.S.S. Omaha - 300 sonic soundings in North Pacific between Strait of Juan de Fuca and Alaska, crossing 49° 21' 20" N in 126° 57' 20" W, 54° 29' 30" N in 154° 31' W, and 52° 07' 15" N in 176° 00' W.

U.S.S. Quail - 220 sonic soundings en route Kiska Harbor to Dutch Harbor, Unalaska, crossing 52° 03' 50" N in 177° 45' 25" W, 52° 30' 35" N in 174° 49' 55" W, and 54° 07' 12" N in 166° 34' 32" W.

U.S.S. California - 265 sonic soundings en route Midway Island to Pearl Harbor and San Diego, California, crossing 27° 35!1 N in 177° 05!6 W, 21° 15' N in 158° 14' W, 28° 35!9 N in 133° 37!9 W, and 32° 50!8 N in 117° 39!9 W.

U.S.S. Saratoga - 75 sonic soundings in North Pacific near Midway Island, crossing 26° 32' N in 179° 12' W, 27° 33' N in 176° 44' W, and 15° 28' N in 167° 30' W.

U.S.S. California - 47 sonic soundings en route San Francisco, California, to Strait of Juan de Fuca, crossing 40° 18' N in 125° 56!5 W, 46° 45!4 N in 126° 23' W, and 47° 40!2 N in 126° 54!5 W.

U.S.S. Farragut - 15 sonic soundings in North Pacific in Hecate Strait, crossing 52° 26' 30" N in 130° 41' 30" W, and 52° 46' 45" N in 131° 20' 30" W.

U.S.S. Bushnell - 800 sonic soundings in Hawaiian Island Area and en route San Pedro, California, through the Canal Zone and Atlantic Coast, crossing 24° 20' 30" in 158° 47' 30" W, 26° 33' 45" N in 168° 15' 00" W, 32° 22' 30" N in 117° 10' 00" W, 18° 24' 30" N in 104° 12' 00" W, 7° 05' 30" N in 80° 35' W, 9° 30' 30" N in 79° 56' 00" W, 13° 26' 30" N in 77° 39' 00" W, and 40° 57' 00" in 71° 56' 00" W.

U.S.S. Sandpiper - 106 sonic soundings en route Amchitka Island, Aleutian Islands, to Arguello, California, crossing 50° 55' N in 178° 30' E, 50° 17' N in 162° 36' W, 44° 48' N in 140° 13' W, and 35° 21' N in 122° 11' W.

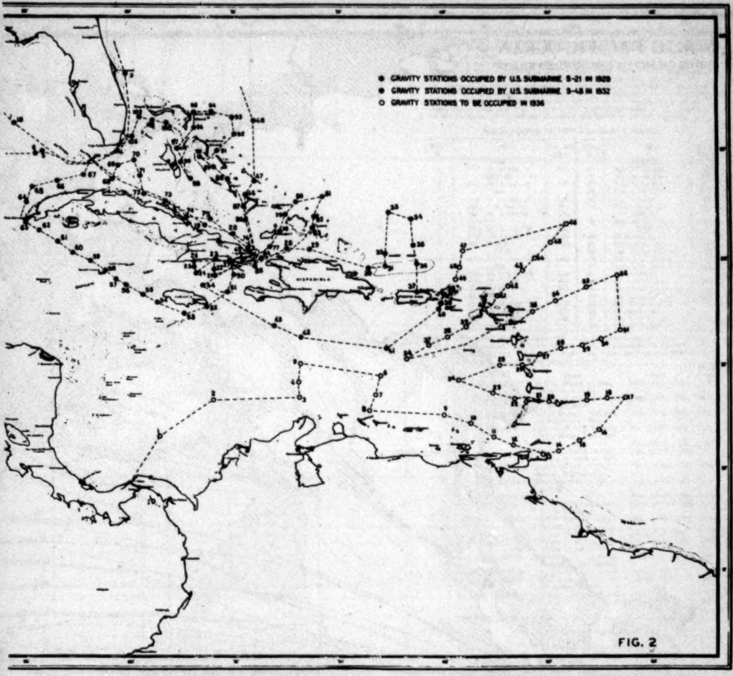

● GRAVITY STATIONS OCCUPIED BY U.S. SUBMARINE S-21 IN 1928
● GRAVITY STATIONS OCCUPIED BY U.S. SUBMARINE S-48 IN 1932
○ GRAVITY STATIONS TO BE OCCUPIED IN 1936
HISPANIOLA

FIG. 2

U.S.S. Oglala - 139 sonic soundings en route Puget Sound, Washington, to Kiska Island, Aleutian Islands, crossing 49° 36' 30" N in 128° 23' 00" W, 53° 54' N in 156° 23' W, and 52° 55' N in 179° 00' W.

U.S.S. Oglala - 196 sonic soundings en route Kiska Harbor, Aleutian Islands, to Navy Yard, Puget Sound, Washington, crossing 51° 27' 45" N in 179° 42' 30" E, 53° 12' 15" N in 157° 41' W, and 48° 58' 45" N in 126° 54' W.

U.S.S. Bushnell - 400 sonic soundings obtained en route Portsmouth, Virginia, to Cristobal, Canal Zone, and San Diego, California, crossing 36° 56' 00" N in 75° 51' 00" W, 21° 51' 20" N in 74° 14' 30" W, 12° 25' 00" N in 78° 20' 00" W, 10° 16' 00" N in 79° 24' 30" W, 7° 23' 00" N in 82° 20' 30" W, 15° 17' 00" N in 98° 01' 20" W, and 32° 20' 30" N in 117° 14' 20" W.

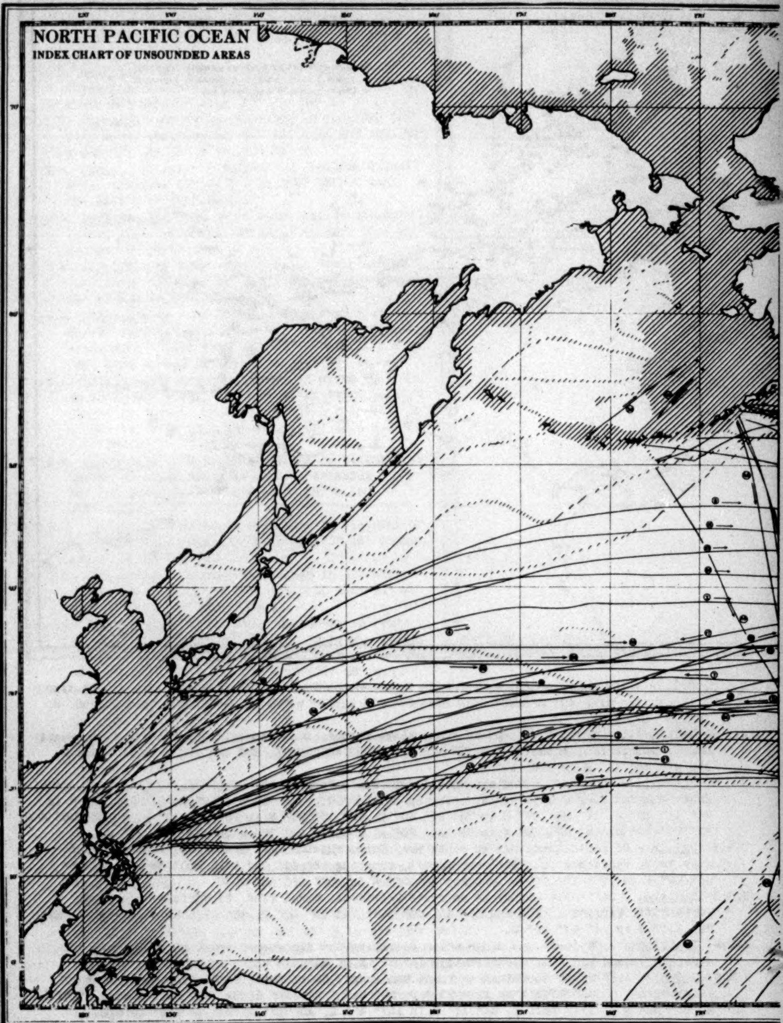
U.S.S. Oglala - 95 sonic soundings en route Navy Yard, Puget Sound, Bremerton, Washington, to Navy Yard, Pearl Harbor, Territory Hawaii, crossing 48° 01' 00" N in 125° 55' 45" W, 34° 54' 00" N in 145° 26' 00" W, and 21° 38' 00" N in 157° 25' 00" W.

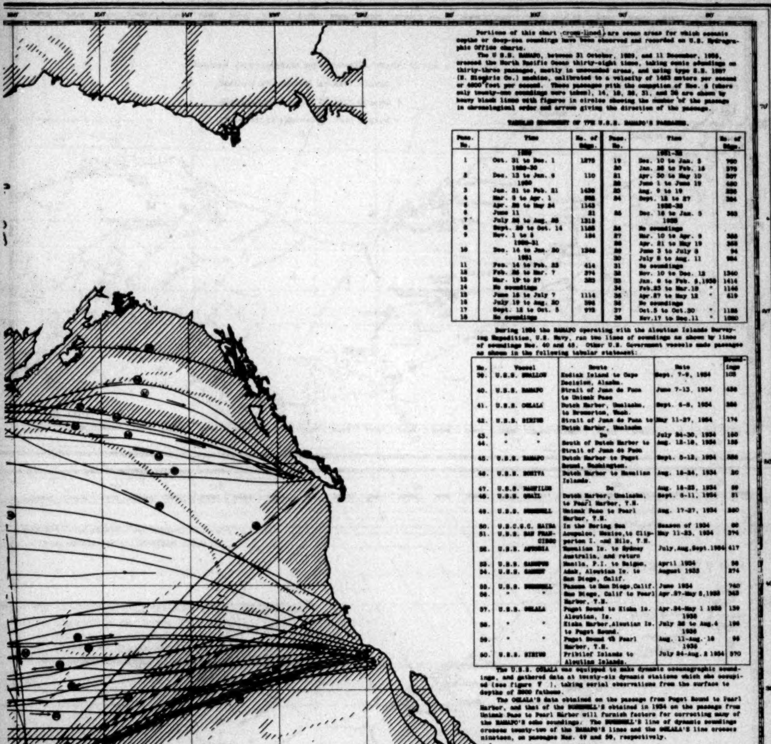
U.S.S. Hannibal - 245 sonic soundings en route Cristobal, Canal Zone, to Norfolk Navy Yard, Portsmouth, Virginia, crossing 10° 44' 00" N in 79° 10' 00" W, 15° 57!6 N in 75° 46' W, and 36° 11!3 N in 74° 47' 00" W.

U.S.S. Tuscaloosa - 90 sonic soundings while surveying the discovered shoal of 28 fathoms off Desirade Island Light in approximately 16° 21' N in 61° 01' W.

U.S.S. Ramapo - 1186 sonic soundings en route San Pedro, California, to Manila, Philippine Islands, crc [illegible] 33° 27!8 N in 121° 23!8 W, 29° 01' N in 158° 51' W, 27° 32!5 N in 179° 21!5 W, 26° 52' N [illegible] 171° 48!5 E, 24° 11' N in 157° 40' E, and 13° 07!7 N in 125° 14!5 E.

U.S.S. Ramapo - 1080 sonic soundings en route Manila, Philippine Islands, to San Diego, California, crossing 19° 45' N in 122° 47' E, 27° 10!8 N in 144° 52!4 E, 32° 30' N in 176° 42' E, 32° 31!5 N in 172° 12' W, and 34° 09' N in 123° 21' W.


NORTH PACIFIC OCEAN
INDEX CHART OF UNSOUNDED AREAS



Portions of this chart (cross-lined) are ocean areas for which sonic depths or deep-sea soundings have been observed and recorded on U.S. Hydrographic Office charts.

The U.S.S. RAMAPO, between 31 October, 1929, and 11 December, 1934, crossed the North Pacific Ocean thirty-eight times, taking sonic soundings on thirty-three passages, mostly in unsounded areas, and using type S.B. 1907 (S. Electric Co.) machine, calibrated to a velocity of 1463 meters per second or 4800 feet per second. These passages with the exception of Nos. 6 (where only twenty-one soundings were taken), 14, 18, 26, 31, and 36 are shown by heavy black lines with figures in circles showing the number of the passage in chronological order and arrows giving the direction of the passage.

TABULAR STATEMENT OF THE U.S.S. RAMAPO'S PASSAGES.

Pass. No.	Time	No. of Sdgs.	Pass. No.	Time	No. of Sdgs.
	1929			1931-32	
1	Oct. 31 to Dec. 1	1275	19	Dec. 10 to Jan. 5	750
	1929-30		20	Jan. 26 to Feb. 16	379
2	Dec. 13 to Jan. 6	110	21	Apr. 30 to May 10	307
	1930		22	June 1 to June 19	480
3	Jan. 21 to Feb. 21	1436	23	Aug. 9 to 19	226
4	Mar. 9 to Apr. 1	988	24	Sept. 12 to 27	364
5	Apr. 26 to May 24	1143		1932-33	
6	June 11	21	25	Dec. 16 to Jan. 5	363
7	July 26 to Aug. 26	1313		1933	
8	Sept. 29 to Oct. 14	1165	26	No soundings	
9	Nov. 1 to 8	184	27	Mar. 10 to Apr. 9	368
	1930-31		28	Apr. 21 to May 19	368
10	Dec. 14 to Jan. 20	1340	29	June 3 to July 8	94
	1931		30	July 8 to Aug. 11	984
11	Feb. 14 to Feb. 23	414	31	No soundings	
12	Feb. 26 to Mar. 7	374	32	Nov. 10 to Dec. 12	1340
13	Mar. 19 to 27	383	33	Jan. 6 to Feb. 5,1934	1414
14	No soundings		34	Feb.23 to Mar.18 "	1146
15	June 16 to July 7	1114	35	Apr.27 to May 12 "	619
16	July 19 to Aug. 20	396	36	No soundings	
17	Sept. 12 to Oct. 5	972	37	Oct.5 to Oct.30 "	1188
18	No soundings		38	Nov.17 to Dec.11 "	1080

During 1934 the RAMAPO operating with the Aleutian Islands Surveying Expedition, U.S. Navy, ran two lines of soundings as shown by lines of soundings Nos. 40 and 45. Other U.S. Government vessels made passages as shown in the following tabular statement:

No.	Vessel	Route	Date	Soundings
39.	U.S.S. SWALLOW	Kodiak Island to Cape Decision, Alaska.	Sept. 7-8, 1934	105
40.	U.S.S. RAMAPO	Strait of Juan de Fuca to Unimak Pass	June 7-13, 1934	438
41.	U.S.S. OGLALA	Dutch Harbor, Unalaska, to Bremerton, Wash.	Sept. 6-8, 1934	388
42.	U.S.S. SIRIUS	Strait of Juan de Fuca to Dutch Harbor, Unalaska	May 11-27, 1934	174
43.	" "	Do	July 24-30, 1934	160
44.	" "	South of Dutch Harbor to Strait of Juan de Fuca	Aug. 12-18, 1934	188
45.	U.S.S. RAMAPO	Dutch Harbor to Puget Sound, Washington.	Sept. 5-12, 1934	588
46.	U.S.S. BONITA	Dutch Harbor to Hawaiian Islands.	Aug. 18-24, 1934	30
47.	U.S.S. NAUTILUS	Do	Aug. 18-23, 1934	69
48.	U.S.S. QUAIL	Dutch Harbor, Unalaska, to Pearl Harbor, T.H.	Sept. 6-11, 1934	51
49.	U.S.S. BUSHNELL	Unimak Pass to Pearl Harbor, T.H.	Aug. 17-27, 1934	880
50.	U.S.C.G.C. HAIDA	In the Bering Sea	Season of 1934	66
51.	U.S.S. SAN FRANCISCO	Acapulco, Mexico, to Clipperton I. and Hilo, T.H.	May 11-23, 1934	376
52.	U.S.S. ASTORIA	Hawaiian Is. to Sydney Australia, and return	July,Aug,Sept.1934	417
53.	U.S.S. CANOPUS	Manila, P.I. to Saigon.	April 1934	56
54.	U.S.S. GANNET	Adak, Aleutian Is. to San Diego, Calif.	August 1933	274
55.	U.S.S. BUSHNELL	Panama to San Diego, Calif.	June 1934	760
56.	" "	San Diego, Calif to Pearl Harbor, T.H.	Apr.27-May 5,1936	363
57.	U.S.S. OGLALA	Puget Sound to Kiska Is. Aleutian, Is.	Apr.24-May 1 1936 1936	139
58.	" "	Kiska Harbor, Aleutian Is. to Puget Sound.	July 26 to Aug.4 1936	196
59.	" "	Puget Sound to Pearl Harbor, T.H.	Aug. 11-Aug. 18 1936	96
60.	U.S.S. SIRIUS	Pribilof Islands to Aleutian Islands.	July 24-Aug. 2 1934	370

The U.S.S. OGLALA was equipped to make dynamic oceanographic soundings, and gathered data at twenty-six dynamic stations which she occupied (see figure V), taking serial observations from the surface to depths of 2000 fathoms.

The OGLALA'S data obtained on the passage from Puget Sound to Pearl Harbor, and that of the BUSHNELL'S obtained in 1934 on the passage from Unimak Pass to Pearl Harbor will furnish factors for correcting many of the RAMAPO'S echo soundings. The BUSHNELL'S line of dynamic soundings crosses twenty-two of the RAMAPO'S lines and the OGLALA'S line crosses nineteen, on passages Nos. 49 and 59, respectively.

FIG. 3

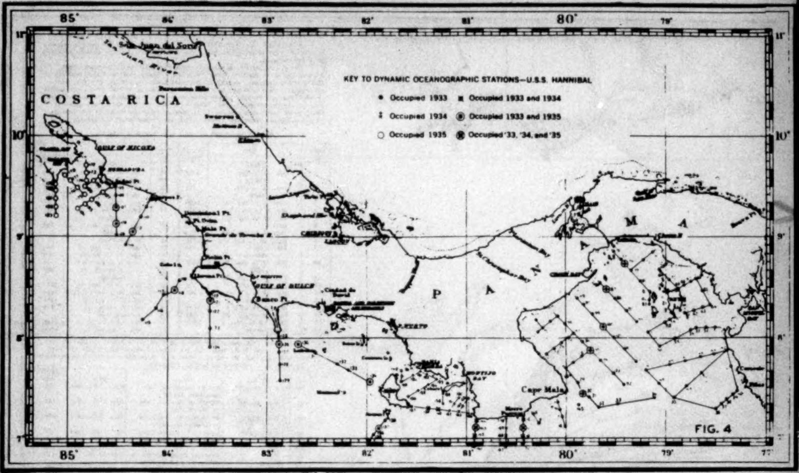

KEY TO DYNAMIC OCEANOGRAPHIC STATIONS—U.S.S. HANNIBAL
● Occupied 1933
■ Occupied 1933 and 1934
‡ Occupied 1934
⊛ Occupied 1933 and 1935
○ Occupied 1935
⊗ Occupied '33, '34, and '35
COSTA RICA
PANAMA
Gulf of Nicoya
Gulf of Dulce
Cape Mala
San Juan del Norte
San Juan River
85°
84°
83°
82°
81°
80°
79°
11°
10°
9°
8°
7°

FIG. 4

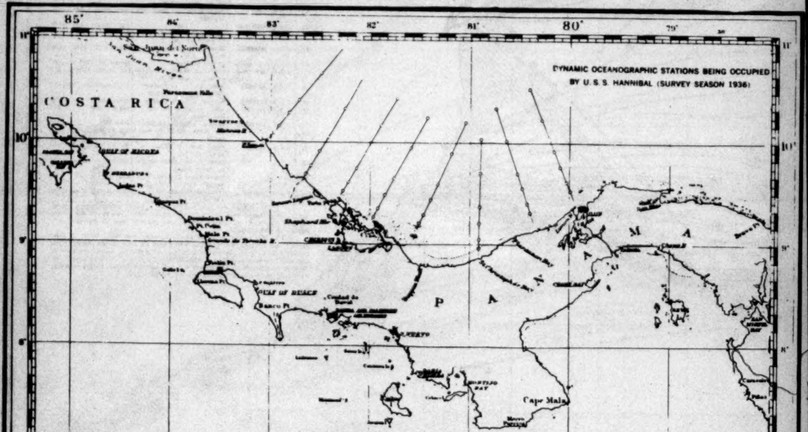

DYNAMIC OCEANOGRAPHIC STATIONS BEING OCCUPIED BY U.S.S. HANNIBAL (SURVEY SEASON 1936)
COSTA RICA
PANAMA
Gulf of Nicoya
Gulf of Dulce
Cape Mala
San Juan del Norte
San Juan River
85°
84°
83°
82°
81°
80°
79°
11°
10°
9°
8°
7°

FIG. 5

Oceanic depths--The Hydrographic Office has recently published Hydrographic Office Publication No. 210E, "List of oceanic depths in the Pacific Ocean, 1932 to 1934, inclusive." This is the sixth of a series of annual publications presenting lists of oceanic depths published by the Hydrographic Office and contains 4800 soundings, among which are 3100 soundings recorded by the U.S.S. Ramapo in seven trans-Pacific passages. The previously published annuals were Nos. 210, 210A, 210B, 210C, and 210D, containing soundings taken in the North Atlantic, North Pacific, Pacific, Atlantic, and Caribbean Sea, and North Pacific oceans, respectively.

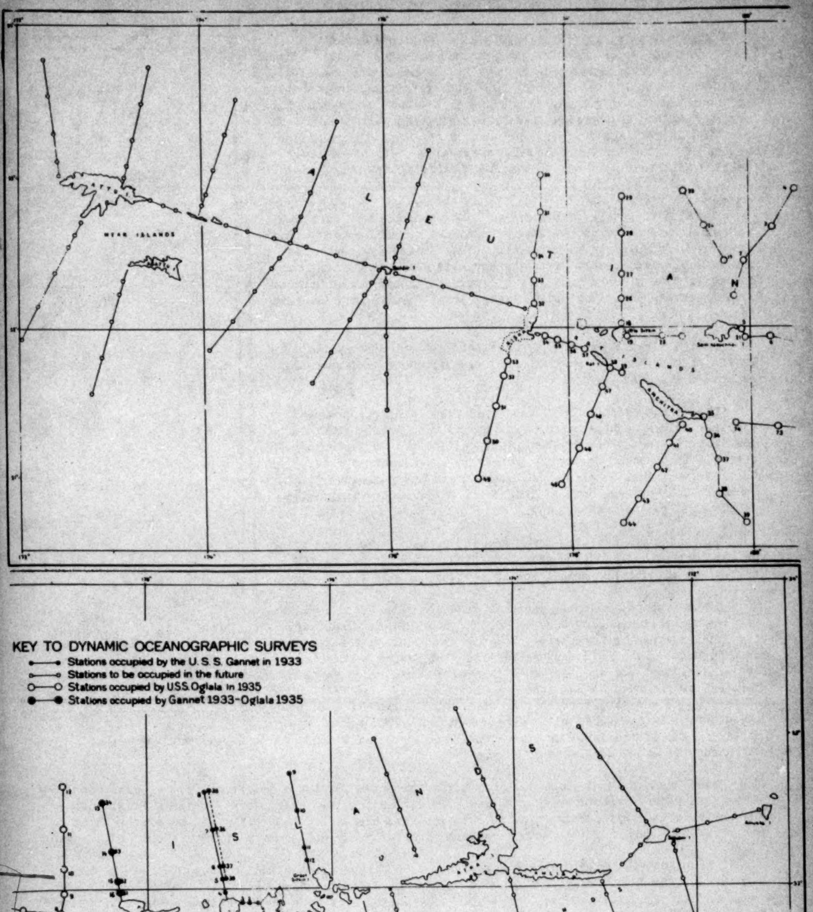

KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS
Stations occupied by the U. S. S. Gannet in 1933
Stations to be occupied in the future
Stations occupied by U.S.S. Oglala in 1935
Stations occupied by Gannet 1933-Oglala 1935
A L E U T I A N
I S L A N D S
NEAR ISLANDS
ATTU
AMCHITKA

FIG. 8

Gravimetric surveying expedition--In cooperation with the American Geophysical Union of the National Research Council of the United States, the United States Navy will endeavor to complete, during December 1936 and January 1937, the investigations relating to the intensity of gravity and depths in the Gulf of Mexico, Caribbean Sea, and in the West Indies, begun by the Navy-Carnegie Expedition in 1928 and further continued by the Navy-Princeton Expedition of 1932. The American Philosophical Society of Philadelphia is contributing funds to assist in carrying out this expedition.

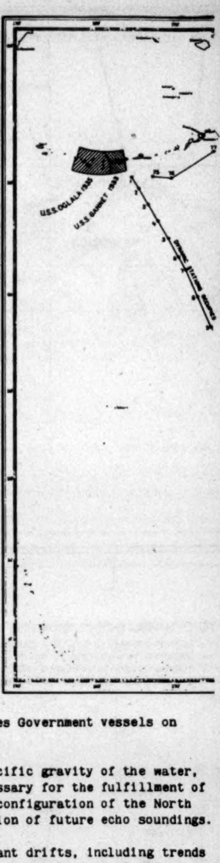
This third gravimetric survey will be conducted as were the two previous expeditions by utilizing a Navy submarine, and using the ingenious multiple pendulum-apparatus devised and perfected by Dr. F. A. Vening Meinesz of the Netherlands Geodetic Commission. The radio time-signals necessary for conducting the investigation will be furnished by the United States Naval Observatory, Washington, D. C.

On the first expedition 50 gravimetric stations were occupied; on the second, 53; and in this third expedition it is proposed to occupy 49 stations (Fig. 2).

The results of the first two expeditions cleared up many doubtful points regarding the stability of the Earth's crust in the area covered by the Greater Antilles, and the projected expedition will no doubt determine whether in the Lesser Antilles Area the gravity-anomalies along the island-chain are analogous to those found in the Netherlands East Indies and consequently indicative of the same general characteristics.

Unsounded areas of the North Pacific Ocean--In 1929 the floor of the North Pacific Ocean, except for the waters bordering its coasts and along a few well-traveled routes, was but little known.

Since then the U.S.S. Ramapo has made 38 trans-Pacific passages and obtained 23,667 echo soundings in areas where but very few soundings had been recorded before. The lines of the Ramapo's soundings have been laid down on the chart of Figure 3 on which the hatched portions are for areas for which soundings have been observed or recorded on Hydrographic Office charts. In addition to the Ramapo's passages across the North Pacific, there are shown two other of her passages while attached to the Aleutian Islands Surveying Expedition in 1934; also 20 passages by other United States Government vessels on which they recorded 5300 echo soundings.



These echo soundings are gradually being corrected for the specific gravity of the water, slope, and other corrections that they may be of the precision necessary for the fulfillment of the desire of the Hydrographer that a comprehensive picture of the configuration of the North Pacific may be had, and the factors gathered for the ready utilization of future echo soundings.

Current-charts--Quarterly presentations of the traverse resultant drifts, including trends and tendencies of the resulting currents in the one-degree quadrangles in the North Pacific Ocean deduced from the observations of the cooperating observers of the Hydrographic Office for the years 1904-24, inclusive, have been completed. They have contributed much to the expediency and safety of surface-navigation as well as aerial navigation.

Work of a similar nature has been begun covering the waters of the Gulf of Mexico, Caribbean Sea, off the East Coast of the Bahamas, and in the Greater and Lesser Antilles--that is, the area within the confines of the Pilot Chart of the Central American Waters.

Mechanical extraction of oceanographic data--The mechanical card-punching of oceanographic data relating to oceanic currents, temperature of the surface-waters, and concomitant data received from our various observers for all oceans and seas has been continued and there are on hand 366,000 punched cards. Some 44,000 of these cards contain data relating to the waters covered by the Pilot Chart of Central American Waters for the month of October from 1925 to 193

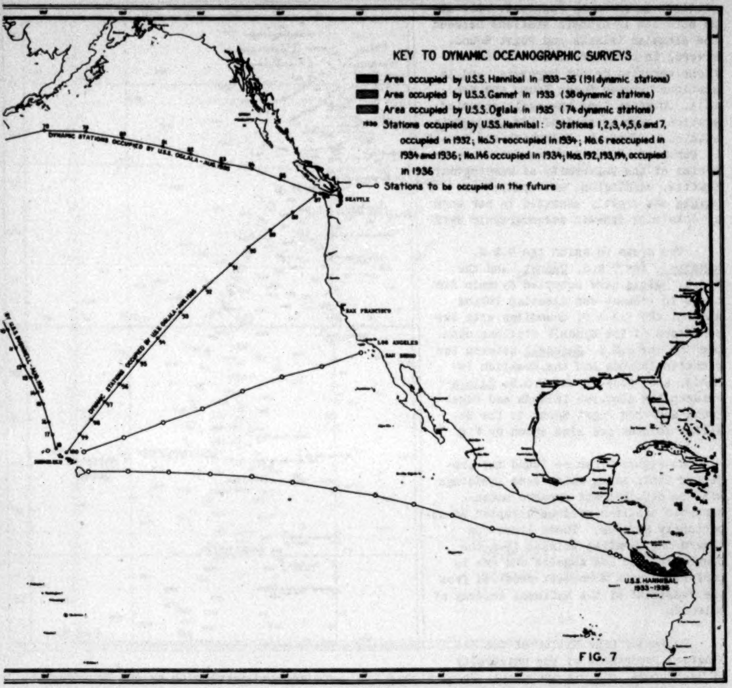

KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS
Area occupied by U.S.S. Hannibal in 1933-35 (191 dynamic stations)
Area occupied by U.S.S. Gannet in 1933 (38 dynamic stations)
Area occupied by U.S.S. Oglala in 1935 (74 dynamic stations)
Stations occupied by U.S.S. Hannibal: Stations 1,2,3,4,5,6 and 7, occupied in 1932; No.5 reoccupied in 1934; No.6 reoccupied in 1934 and 1936; No.146 occupied in 1934; Nos. 192,193,194, occupied in 1936
Stations to be occupied in the future
SEATTLE
SAN FRANCISCO
LOS ANGELES
SAN DIEGO
HONOLULU
U.S.S. HANNIBAL 1933-1936
DYNAMIC STATIONS OCCUPIED BY U.S.S. OGLALA

FIG. 7

The University of California has sponsored a project approved by the Works Progress Administration for the evaluation of oceanographic data relating to oceanic currents and temperatures of the Pacific Ocean that have been reported by the cooperating observers of the Hydrographic Office subsequent to 1924.

Work under this project has been started under the superintendency of Dr. T. Wayland Vaughan, Director of the Scripps Institution of Oceanography, La Jolla, California, and the Officer in Charge of the Branch Hydrographic Office, San Pedro, California, and it is expected that the results will constitute a splendid and much-needed accession to the existing knowledge of the circulation and cognate phenomena of the Pacific Ocean.

Dynamic oceanographic surveys--The U.S.S. Hannibal occupied 36 dynamic stations on the Pacific Coast of Panama and Costa Rica. Five of these stations in the Gulf of Panama were previously occupied in 1933 and 1934; eleven of these stations were off the Coast of Panama, two of which had been occupied in 1933; and 20 stations were in the Gulf of Nicoya and approaches (see Fig. 4).

In all, the Hannibal has occupied 191 dynamic stations in the three years of her work in the above areas. During this season's work on the East Coast of Panama the Hannibal has already occupied 20 dynamic stations, two of which she had previously occupied (see Fig. 5).

The U.S.S. Oglala assisting with the United States Naval Aleutian Islands Surveying Expedition occupied several dynamic stations previously occupied by the U.S.S. Gannet and 74 other stations as shown by Figure 6. She also occupied 12 dynamic stations between the Aleutian Islands and Puget Sound, several in close proximity to the stations occupied by the Carnegie, and 14 stations between Puget Sound and Honolulu, on which line she again occupied stations near several of the Carnegie's stations. James R. Galbraith and Robert L. Hurlbert of the Oceanographic Laboratories of the University of Washington, Seattle, Washington, accompanied the Oglala and greatly assisted in her work of obtaining dynamic oceanographic data.

The areas in which the U.S.S. Hannibal, the U.S.S. Gannet, and the U.S.S. Oglala have occupied dynamic stations in Panaman and Aleutian Island waters, the lines of soundings with the positions of the dynamic stations occupied by the U.S.S. Bushnell between the Aleutian Islands and the Hawaiian Islands, and those of the U.S.S. Oglala between the Aleutian Islands and Puget Sound and from Puget Sound to the Hawaiian Islands are also shown by Fig. 7.

On Figure 7 can be found two projected lines along which some soundings will be obtained and dynamic oceanographic stations will be occupied as opportunity affords. These lines run toward the Hawaiian Islands from the Canal Zone and Los Angeles and are in conformity with a request received from the President of the National Academy of Sciences.

Professor Loye Miller of the Biological Department of the University of California, and his assistant, Frank Richardson, were granted permission by the Navy Department to accompany the U.S.S. Nokomis surveying in Colombian waters.

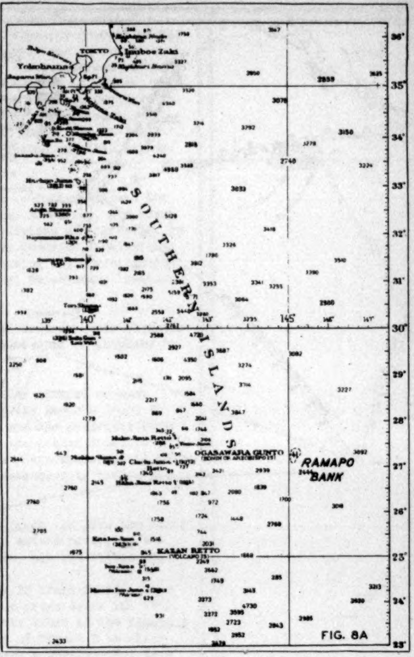
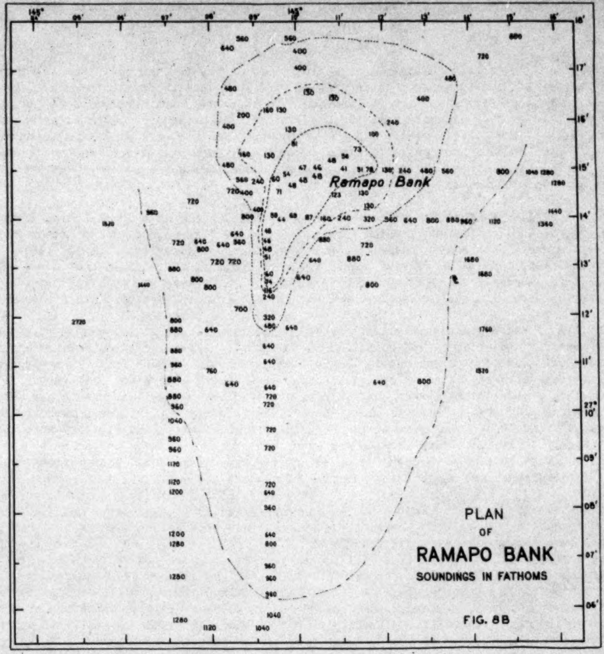


FIG. 8A

The so-called Bjerknes method of hydrodynamic surveys applied to certain of the dynamic data obtained by the U.S.S. Hannibal has proven that the currents along the West Coast of Panama and Costa Rica previously determined by the differences between the positions ascribed to a dead-reckoning position and a position determined by stellar or other astronomical fixes as shown on the Pilot Chart of the North Pacific Ocean are of similar order.

The Hydrographer appreciates the valuable and continued cooperation of the Scripps Institution of Oceanography, La Jolla, California, the Oceanographic Laboratories of the University of Washington, Seattle, Washington, and the Department of Terrestrial Magnetism, Carnegie Institution of Washington, D. C., in these dynamic oceanographic surveys.

Ramapo Bank--The Ramapo on a recent trans-Pacific passage obtained a shallow echo-sounding of slightly over 40 fathoms to the eastward of the Ogasawara Islands, where previous and scanty soundings indicated a submerged plateau of some 3000 fathoms. In furtherance of advice from the Hydrographic Office, the Ramapo retraced her passage over the previously observed shoal sounding and developed the surrounding area by a number of echo soundings, finding a well-defined bank with a least depth over it of 41 fathoms rising rapidly from a bottom floor of 1000 fathoms in an average distance of four miles. The Ramapo's echo soundings and their geographical positions relative to the Ogasawara Islands and Japanese Islands are shown on Figure 8. The bank will be named Ramapo Bank and will become another aid to navigation in that part of the North Pacific Ocean.



PLAN
OF
RAMAPO BANK
SOUNDINGS IN FATHOMS

FIG. 8B

__Magnetic charts__--The Hydrographic Office has published and has on issue world charts showing the values of the magnetic elements for the epoch 1935 as indicated in last year's report to the American Geophysical Union. These charts as issued cover all land- and sea-areas. The Carnegie Institution of Washington, D. C., supplied most of the data used for their construction.

In furtherance with the often expressed wish of my predecessor in charge of the Hydrographic Office, I offer the hope that we in this country will build and equip another __Carnegie__ for conducting the magnetic and other scientific work at sea so necessary for safe and expedient navigation.

The Hydrographic Office will welcome the opportunity to make available to members of the Union such information as it may possess which might be of interest or service in connection with any of their investigations.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

R. P. Eyman

The oceanographic work of the Coast and Geodetic Survey for the past year is largely represented in the offshore surveys on the Atlantic, Gulf, and Pacific coasts, together with additional areas in western Alaska and the Philippines. These surveys are proceeding as rapidly as conditions permit to procure accurate data for the construction of modern charts along our coasts out to the limits of the coastal shelf. In the prosecution of this work many data are obtained, more or less as a by-product incidental to these surveys, that are of interest to the oceanographer, such as serial temperatures and salinities, water- and bottom-samples, and investigations into the propagation of sound-wave travel in sea-water.

In the earlier surveys the offshore work consisted largely of a few sounding lines run out to the edge of the coastal shelf which were controlled by dead-reckoning and astronomical sights, supplemented where possible by buoys located somewhat more rigidly than the individual sounding lines. The results of these surveys, while adequate for the navigator at that time, were not sufficient for modern charts to be used by present-day ships having much higher speeds, and which are equipped with the latest improvements in echo-sounding devices, radio compasses, etc.

In view of these demands an attempt is being made in our recent surveys to obtain a much greater density (and accuracy) of soundings as well as to delineate the submarine topography more faithfully and to more accurately locate these soundings. These criteria are now more readily and economically attained by the use of echo-sounding apparatus, radio-acoustic ranging, and taut-wire measurements between control-buoys, all of which have been previously described in former papers. Our present efforts along these lines are constantly to seek improvements in these methods and to overcome some of the difficulties and limitations at first encountered. In order properly to evaluate data obtained in these operations, numerous temperature- and salinity-observations must be (and have been) obtained and various experimental observations made to determine as accurately as possible the velocity of sound in sea-water.

On the east coast of the United States the survey ships Oceanographer, Lydonia, Gilbert, and Welker, working as one unit, completed a section this past season off the entrance to Chesapeake Bay covering an area of about 5500 square miles (see Fig. 1). The outer edge of this Area shows several submarine valleys that will prove of great interest and value to the geologist and the navigator (see Fig. 2). As an example of the latter, an excerpt from the report of the Commanding Officer of the Oceanographer is cited. Early this past season it was desired to have some additional reconnaissance-work done around one of these valleys (located the previous season) before the rigid control could be carried out to the Area by the parties. In order to do this, the Commanding Officer of the Oceanographer states in his report that the Oceanographer and Lydonia proceeded to the area some 65 miles northeastward from the Bay entrance where a short but unsuccessful search was made for the small spar-buoys marking the wreck of the Merida, located the previous season; as these buoys are small and of low visibility not much time was spent in the search, but instead the ships proceeded to the vicinity of the northern tip of the valley as delineated by the 200-fathom curve which, as determined by the survey of 1934, is quite well defined. By sounding, this tip was soon found and used as a departure point for a short run inshore into shoaler water for the planting of a mooring buoy for the station-ship; this mooring buoy was then easily tied in to the easternmost Merida wreck-buoy by taut-wire measurement; however, before accomplishing much work, adverse weather-conditions forced the ships to discontinue work altogether. Work could not again be resumed for about two weeks when it was found that the station-buoy had been carried away and the former procedure was repeated in planting and locating a second mooring buoy. After relocation this second buoy was then found to be within about 15 meters of the site of the previous buoy and later in the season, after rigid control had been extended throughout the Area and the above buoys had been again checked, there was found to be no appreciable difference from the original determination.

Work for the coming season is planned for these four ships, as a unit, in the area off the entrance to New York Harbor where much additional and valuable information should be obtained.

On the Gulf Coast the Hydrographer, assisted by two 75-foot launches acting as station-ships, has continued surveys off the Louisiana coast out to the 100-fathom curve eastward from previous work, covering about 5300 square miles. Here again there are evidences, not at present fully investigated, of offshore submarine valleys.

On the Pacific Coast the Pioneer and the Guide have continued work off the southern California coast with a party from the Guide wire-dragging the inshore areas out to about 20 to 30 fath-

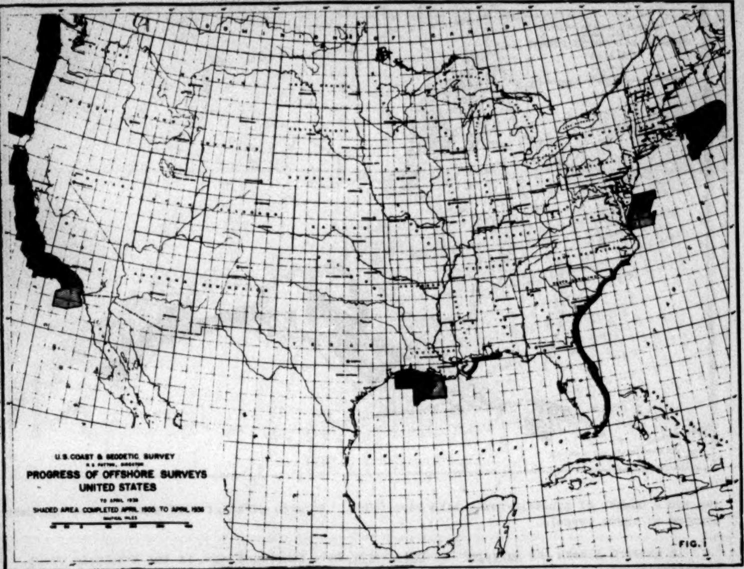

U.S. COAST & GEODETIC SURVEY
R.S. PATTON, DIRECTOR
PROGRESS OF OFFSHORE SURVEYS
UNITED STATES
TO APRIL 1936
SHADED AREA COMPLETED APRIL 1935 TO APRIL 1936
NAUTICAL MILES

FIG. 1

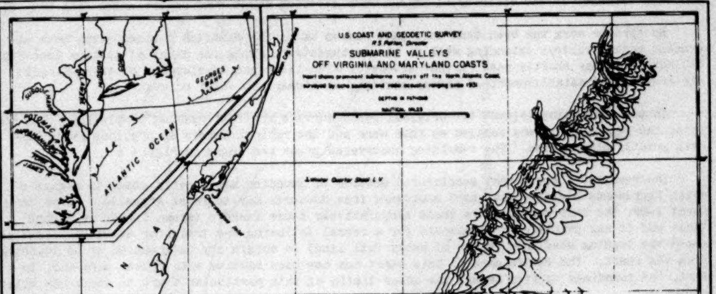

U.S. COAST AND GEODETIC SURVEY
R.S. Patton, Director
SUBMARINE VALLEYS
OFF VIRGINIA AND MARYLAND COASTS
Inset shows prominent submarine valleys off the North Atlantic Coast, surveyed by echo sounding and radio acoustic ranging since 1931
DEPTHS IN FATHOMS
NAUTICAL MILES
GEORGES BANK
HUDSON R.
POTOMAC
JAMES R.
ATLANTIC OCEAN
VIRGINIA
CAPE CHARLES
CAPE HENRY
CHESAPEAKE BAY ENTRANCE

FIG. 2

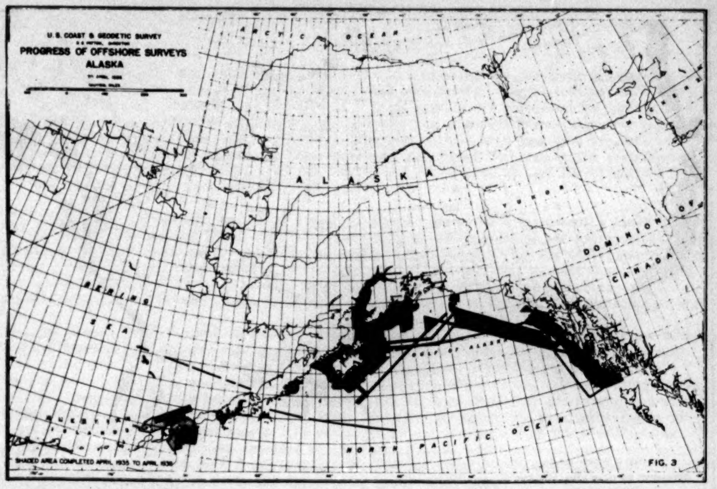


FIG. 3

oms and a number of pinnacle-rocks have been found. An area of about 7900 square miles has been covered by these vessels.

In western Alaska the Surveyor and Discoverer have continued work in the Krenitzin Group, Aleutian Islands, in the vicinity of Unimak Pass covering about 4500 square miles (see Fig. 3).

No further work has been done this past season among the Hawaiian Islands which have at present modern surveys extending well to the northwestward along the chain of islands (see Fig. 4), but which may shortly need further extension with the rapid development of trans-Pacific air-traffic and establishment of airway-stations at Midway and other points.

In the Philippine Islands the original basic surveys are fast nearing completion. But one ship, the Fathomer, is now engaged on this work and the rapid progress of previous years has been greatly slowed down. The remaining unsurveyed areas are shown in Figure 5.

The results of our recent accelerated methods of sounding are clearly shown in Figure 6 which represents a west-coast chart southward from Monterey Bay to Point Arguello. Prior to about 1929, the only surveys were those comparatively close inshore (shown inside of dashed line) and it was practically impossible for a vessel following the track for about 120 miles between the leading headlands (shown by heavy full line) to obtain any information as to soundings from the chart. The entire area of this chart has now been covered with recent work and, in fact, the soundings carried beyond the outer limits of this particular chart to about 120 miles offshore.

Improved methods and devices to increase the accuracy and speed of survey-work are being sought constantly. Various investigations are being made to better determine the numerous elements that enter into corrections necessary in this type of control.

Experiments to determine the path and velocity of sound-waves in sea-water have been continued with very interesting results. On the work off Chesapeake Bay entrance, a number of direct measurements were made in depths from 15 to 30 fathoms which indicated that the theoretical velocity of sound through sea-water, corrected for bottom-temperatures and salinities, agreed with the observed values to within about one meter per second for these depths.

Off the California coast the Pioneer and the Guide continued a number of experiments started

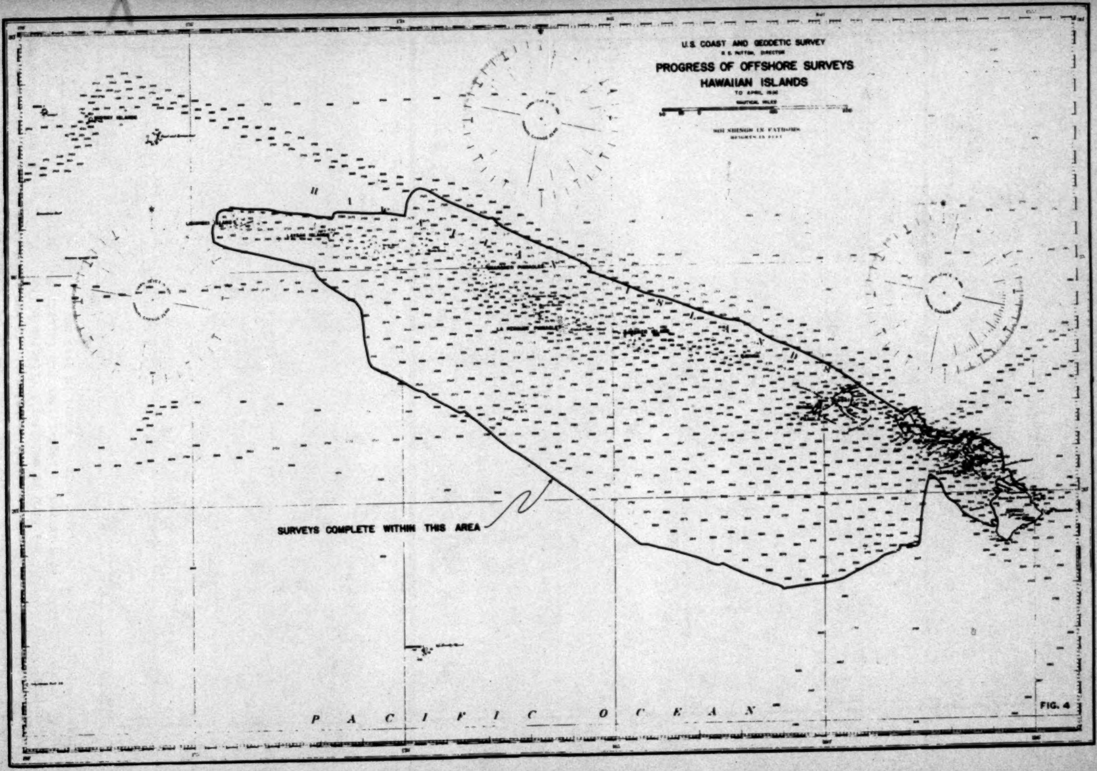

U.S. COAST AND GEODETIC SURVEY
R. S. PATTON, DIRECTOR
PROGRESS OF OFFSHORE SURVEYS
HAWAIIAN ISLANDS
TO APRIL 1936
NAUTICAL MILES
SOUNDINGS IN FATHOMS
HEIGHTS IN FEET
H I I S L A N D S
SURVEYS COMPLETE WITHIN THIS AREA
P A C I F I C O C E A N

FIG. 4

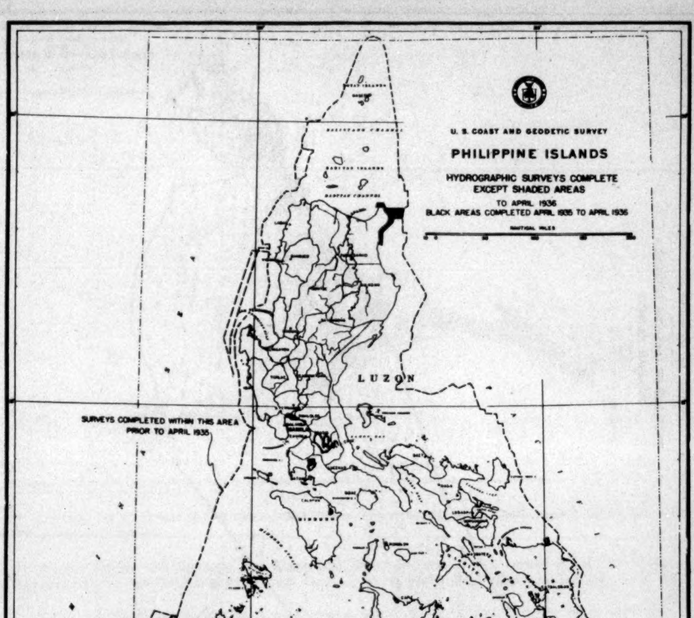

U. S. COAST AND GEODETIC SURVEY
PHILIPPINE ISLANDS
HYDROGRAPHIC SURVEYS COMPLETE EXCEPT SHADED AREAS
TO APRIL 1936
BLACK AREAS COMPLETED APRIL 1935 TO APRIL 1936
NAUTICAL MILES
LUZON
SURVEYS COMPLETED WITHIN THIS AREA PRIOR TO APRIL 1935
BOHOL
SULU SEA
MINDANAO
BORNEO
CELEBES SEA
INTERNATIONAL TREATY LIMITS

FIG. 5

last season to analyze the travel-path of sound in deep water. It was definitely established that the sound travels in a series of reflections and refractions, with some diffraction for short distances, and that the path is materially affected by the even or uneven character of the bottom or steep slopes near the receiving hydrophone. It was found that the sound of a one-pound TNT bomb will travel in a direct line from bomb to hydrophone for a distance of only 9 to

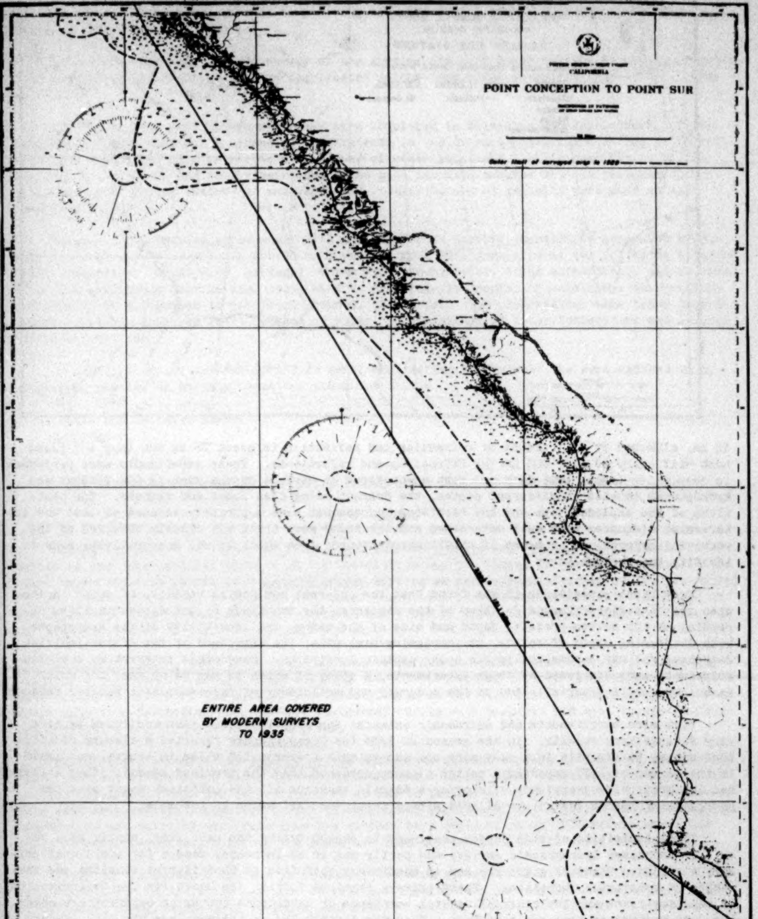

UNITED STATES - WEST COAST
CALIFORNIA
POINT CONCEPTION TO POINT SUR
Outer limit of surveyed area in 1929
ENTIRE AREA COVERED
BY MODERN SURVEYS
TO 1935

FIG. 8

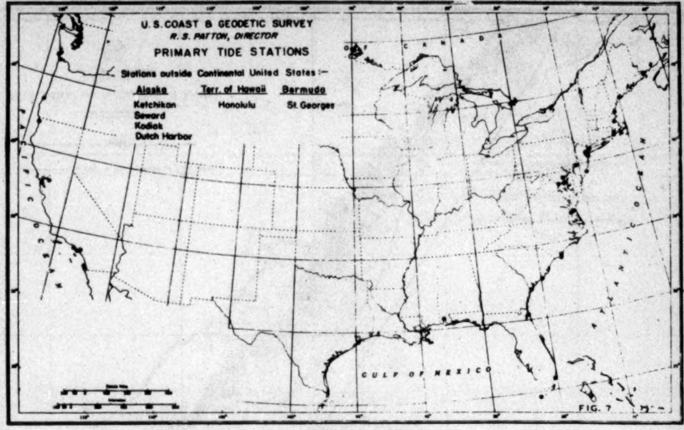


FIG. 7

12 km, although it will travel by refraction and reflection to about 75 km and that a 7-pound bomb will carry to over 300 km (by refraction and reflection). These experiments were performed in deep water (about 1025 fathoms) with bombs fired at various depths down to 800 fathoms and hydrophones located at different depths, the deepest being also about 800 fathoms. The positions of the exploded bomb and the receiving hydrophones were accurately located so that the intervening distances were well determined and the sound-wave train was closely observed on the receiving hydrophones by means of oscillograph-records from which it was comparatively easy to identify the various waves.

From these experiments it was found that the apparent horizontal velocity of sound in the open sea is a discontinuous function of the distance, the magnitude of the discontinuities depending on the bottom-profile, depth and size of the bombs, and sensitivity of the hydrophone. With decreasing depth of bottom, or increasing bomb-size, the magnitude of the discontinuities decreases and may become negligible under certain conditions. Many other interesting and valuable facts were disclosed by these experiments, a study of which is now being made and which it is believed will materially add to the accuracy and efficiency of radio-acoustic ranging methods.

Taut-wire measurements and astronomic azimuths for buoy-locations have continued to give very satisfactory results. In the season of 1934 the Oceanographer reported a closure of about four meters to the mile in a taut-wire and sun-azimuth traverse 115 miles in length, and again in the season of 1935 reported a better closure obtained than the previous season. This writer had the gratifying experience of closing a 50-mile traverse off the Louisiana coast with the Hydrographer during the season of 1934 within about one-half meter to the mile.

Tidal activities of this Bureau continued to expand during the past year, partly as a result of increased hydrographic surveys and partly due to an increased demand for additional primary stations. Standard gages are now in continuous operation at 50 different stations and the number is constantly increasing. These primary stations furnish the basis for the determination of mean sea-level and the study of coastal emergence or subsidence for which observations covering long periods of time are necessary. They are distributed as follows (see Fig. 7): Twenty-four on the Atlantic Coast; 3 on the Gulf Coast; 17 on the Pacific Coast; 5 in Alaska, and one in the Territory of Hawaii. Short series of observations at several hundred additional stations have resulted from the increased hydrographic activities.

The tidal survey of the State of Washington has been completed. Wherever possible, stations occupied in this survey were connected with the precise level-net so that they could be correlated with the Oregon tidal survey previously made. It is now planned to conduct a similar survey of San Francisco Bay ultimately to include the Sacramento and San Joaquin waterways. A special tide-survey of a portion of Delaware Bay has been started in cooperation with the State of

Delaware and a similar survey of Barnegat Bay in cooperation with the State of New Jersey is being planned. This Bureau is also cooperating with the United States Army Engineers in a tidal survey of Galveston Bay.

A combined tide- and current-survey of Los Angeles and Long Beach harbors is now in progress for the purpose of investigating the complicated seiche- and surge-movements prevalent in these waterways.

During the past year, current-surveys were completed in Galveston and Mobile bays. These included for each waterway a series of observations in the entrance covering a period of approximately a month, and shorter series at a number of other locations. Daily predictions of the currents in Galveston and Mobile entrances based upon the data secured will be included in the Atlantic Coast Current Tables for the year 1937. Observations of salinity were made at each current-station.

Through a cooperative arrangement with the Lighthouse Service, continuous series of hourly current-observations covering a period of a year or more were completed at the following Atlantic Coast lightships: Chesapeake, Barnegat, Cross Rip, Handkerchief, Stone Horse Shoal, and Pollock Rip. The Lighthouse Service also cooperated in securing five months of continuous observations of currents at a location in San Pedro Channel, California. The observations were taken from a relief lightship anchored in 60 fathoms of water. Measurements of water-temperature and density were also obtained.

In addition to the current-work just mentioned, series of observations were secured by hydrographic parties at various locations along our coasts.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN 1935 AND PLANS FOR 1936

H. G. Hamlet

During the season of 1935, the Coast Guard cutters Mendota and Pontchartrain carried on the duties of the International Service of Ice Observation and Ice Patrol in the North Atlantic, the Coast Guard 125-foot patrol boat General Greene serving as oceanographic vessel of the Ice Patrol Force. Lieutenant G. Van A. Graves, U.S. Coast Guard, was Ice-Observation Officer in charge of the scientific work of the Ice Patrol cutters, and Floyd M. Soule was Oceanographer in charge of the scientific work of the oceanographic vessel.

As in past years, several thousand surface-temperature reports were received from passing steamers by the patrol cutters, thus enabling the Ice-Observation Officer to maintain an up-to-date isothermal chart of the usually ice-infested area in the vicinity of the Grand Banks. From these data nine fortnightly sea-surface isothermal charts were prepared and will appear in Coast Guard Bulletin No. 25 which is now in press.

During the ice-season the General Greene made three current-surveys of the area immediately south and east of the Grand Banks between March 28 and June 10, 1935, completing the resulting dynamic topographic maps and delivering them at sea to the cutter on patrol after each survey. This work involved the occupation of 167 oceanographic stations at which serial measurements of temperature and salinity were made from the surface to a depth of about 1400 meters where the depth of water permitted, although the immediate interest centered in the upper 1000 meters.

Early in the season there was an unusually eastward spread to the ice drifting south of 48° north latitude. In April the Labrador Current was flowing very swiftly along the eastern edge of the Grand Banks, especially in about latitude 45° north. However, it apparently did not bend westward of about 50° west at the tail of the Banks. About the beginning of May an abrupt change took place in the relative strengths of the Polar Current along the Avalon Peninsula and the Labrador Current along the eastern edge of the Grand Banks, the former waxing and the latter waning. In May the Labrador Current, although weaker than in April, was still strong in about latitude 45° north. A broad intrusion of Gulf Stream water was found with noticeable salients in about 43° 30' north and 45° 30' north. In June this intrusion had decreased in area and was centered at about 44° north. The Labrador Current, although reduced in intensity, was still present along the eastern edge of the Grand Banks. From a hydrodynamic standpoint the season resembled that of 1933 except that the quantity of ice was abnormally and unexpectedly great.

The correlation which exists between winter winds, icebergs, and sea-ice is occasionally disturbed by other little-known factors and it is hoped that we are now on the track of some of these factors. The difficulty is that the improvement of Commander Smith's ice-forecast formulae by considering factors other than barometric pressure-anomalies requires a long series of observations and some of the most promising of these auxiliary factors, such as volume of flow and rate of heat-transport of oceanic currents entering the Labrador Sea, have been observed but a comparatively small number of times.

Upon the conclusion of the Ice Patrol season, the General Greene made an intensive survey of the Labrador Deep and the supposed Newfoundland Ridge. On this survey, between July 10 and August 23, 1935, 110 stations were taken at which temperatures and salinities were measured from surface to bottom. At 12 of these stations, selected to form a section from Cape Farewell southwestward to deep water and thence south-southeastward to a point south of the supposed Newfoundland Ridge, a total of 95 samples were taken for oxygen-determinations and an equal number of helium-samples were taken. Most of these samples were taken from 600 meters to bottom, only a few stations having oxygen- and helium-samples from the upper 600 meters. On this post-season cruise 2036 fathometer-soundings were taken. These have been corrected, tabulated, and supplied to the United States Hydrographic Office and to the International Hydrographic Bureau and form the major basis of a bathymetric chart which has been prepared and appears in the Coast Guard Bulletin No. 25 along with the results of the season's work. The results of the post-season cruise will appear in a future bulletin of the Coast Guard.

Commander Edward H. Smith, Olav Mosby, and Floyd M. Soule are collaborating in the preparation of Coast Guard Bulletin 19, Part 2, dealing with the physical oceanography of the northwestern North Atlantic based on the results of the northern cruises of the Marion in 1928 and the General Greene in 1931, 1933, and 1934. As the preparation of this volume has reached an advanced stage, it is expected that it may be published some time this year.

As this meeting of the Union is in session, the 1936 Ice Observation and Ice Patrol Service is already in operation, having been inaugurated March 27. The General Greene is continuing the work of supplying current-charts to the patrol-cutters as in previous years. Upon the conclusion of the present ice-season, it is intended that the General Greene will make an abbreviated post-season cruise in the waters between southern Labrador and southwestern Greenland reoccupying key-stations taken in previous surveys for the purpose of determining variations in the volume and temperature of the currents.

During the Bering Sea Patrol season of 1934, the Coast Guard, in cooperation with the Oceanographic Laboratories of the University of Washington, made oceanographic observations in the Bering Sea and Arctic Ocean. The completed report, dealing with chemistry of the Bering Sea where investigated, ocean-water, various organisms and plants, currents, and dynamic calculations, is to be published.

In the summer of 1935 the Coast Guard cutter Chelan, in developing a line of soundings previously taken in western Bering Sea, discovered a submerged mountain range extending from Petrel Bank north to Bowers Bank, thence westerly to latitude 55° north, longitude 176° east. This range has a well-defined ridge with hardly a break, approaching the surface in places from 40 to 150 fathoms, but averaging around 300 fathoms. It was observed that, at the western end, the mountains rose abruptly nearly 11,000 feet from an ocean-floor of 2100 fathoms, and that the 1000-fathom area was regular in its width, being about 30 miles. It is the purpose of the Coast Guard to continue the development of the observations taken in this region, as opportunity offers. This vessel also took a series of soundings off the north coast of Attu, Aleutian Islands, contributing to the bathymetrical knowledge of this sparsely surveyed area.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC RESEARCH AT THE SCRIPPS INSTITUTION DURING APRIL 1935 TO APRIL 1936

T. Wayland Vaughan

Expeditions and oceanographic data--The renovations and improvements on the Institution's boat Scripps, mentioned in last year's report, were completed in time for the boat to be used in June, 1935. Particular attention was given to a line of three stations, the depth at the outermost of which is 2000 meters, between Point Loma and the south end of San Clemente Island, a distance of about 60 miles. Some or all of them were occupied in May, July, August, and September, 1935, and January, 1936. Seven stations ranging to 1500 meters in depth were occupied on a trip from San Diego to the Santa Barbara Islands. On another occasion several stations were occupied between the mainland and Tanner Bank and between the northwest end of San Clemente Island and the southeast end of Santa Catalina Island. On the trips to Tanner Bank and on other trips near San Diego and the Coronados Islands, Dr. L. H. Miller accompanied the *Scripps* to make a study of marine birds. The use of the *Scripps* in studies of submarine geology is mentioned elsewhere in this report. Table 1 presents a summary of oceanographic data received at the Institution during the year.

Table 1--*Number of observations of sea-temperatures, salinities, and meteorological conditions received at the Scripps Institution, March 15, 1935, to March 15, 1936*

Group	Station or ship	Salinity	Temperature	Depth meters	Wind	Air-temperature	Remarks
A	Scripps Institution Pier	366(a)	366	0	366	366	Continuous barograph and pyranometer records and daily observations of humidity and precipitation
	Scripps Institution Pier	366(a)	366	5(btm)	...	...	
	Balboa Pier	366(a)	366	0	366	...	
	Hueneme	314(a)	314	0	314	...	
	Pacific Grove	366(a)	366	0	366	...	
	Farallon Islands	366(a)	366	0	...	...	
	Blunts Reef lightship	366(a)	366	0	366	...	
	Drakes Estero, Marin County, California	22(a)	24	..	24	...	
	U.S. Lighthouse tenders, *Sequoia* and *Lupine*	150(a)	1280	0	1280	1280	Water thermograph-records for all coastal trips of *Lupine*
	Rose	103(a)	220	0	220	...	
	Grace Line, Valparaiso to Central American ports	...	2925	0	...	2925	
	Escuela Naval del Perú, La Punta, Callao	...	366	0	366	366	
	Totals	2785(a)	7325	..	3668	4937	
B	U.S.C.G.S.S. *Guide*	23(b)	23	..	...	...	Serial; off southern California
	U.S.C.G.S.S. *Pioneer*	12(b)	12	..	...	...	Serial; off southern California
	Scripps	377(b)	377	..	...	...	Serial; off southern California
		...	532	0	...	...	
	Scripps Institution Pier	117(b)	...	0	...	...	
		46(b)	...	5	...	...	
	Yacht *Velero III* (Capt. Allan Hancock)	92(b)	92	0	...	...	San Diego to Gulf of California
	Yacht *Zaca* (Templeton Crocker)	134(b)	134	0	...	...	San Diego to Gulf of California
	U.S.S. *Hannibal* (1935)	298(b)	317	..	...	...	Serial; off Panama and Costa Rica
	Totals	1109(b)	1487	..	...	...	

Notes: (a) = salinity by specific gravity; (b) = salinity by chlorine titration

Physical oceanography and marine meteorology--George F. McEwen reports that temperatures were averaged from thermograms on the steamers *California*, *Virginia*, and *Pennsylvania* of the Panama Pacific Company according to two-hour intervals, and from these tables temperatures were averaged according to months and half-degree quadrangles for the period May 1932 to November 1934, inclusive, along courses from Panama to San Francisco, California. Thermograms from one instrument on the steamer *Calawaii* of the Los Angeles Steamship Company on courses between San Pedro and Hawaii have been compiled in the same way for the period August 1927 to June 1932. Thermograms from one instrument on the U.S.S. *Ramapo* on various courses in the North Pacific between North America and Asia during the period July 1932 to February 1933, have been similarly compiled. Serial observations of temperature, salinity, and hydrogen-ion concentration have been made at stations 1 and 2, respectively ten and five miles west of the Scripps Institution, for the period 1921 to 1932, mainly from spring to autumn. Computations of smoothed values corresponding to intervals of one-half a month completed in 1933 have all been carefully checked. Rocomputations have been made whenever the need was suggested, and final adjusted values have thus been determined. Gradients and time-rates of these values, together with the densities, have been calculated for use in studies of turbulence and vertical velocity.

McEwen also devoted much attention to seasonal forecasts of precipitation and monthly air and sea-surface temperatures at intervals of three months. Investigations leading to a general temperature "outlook" over longer periods of six months or a year were also continued. Great interest in the forecasting work continued to be expressed by many individuals and organizations. A contribution to methods of testing the statistical significance of cycles used in forecasting, presented in 1934, under the title "The reality of regularities indicated in sequences of observations," was revised and greatly extended. Publication of this paper awaits the results of criticisms and suggestions.

A paper based upon certain methods developed for use in summarizing numerical field-data was presented March 2, 1935, under the title "Note on calculating equally spaced ordinates from averages of observed ordinates arbitrarily spaced" at the Mathematical Association of America meeting in Los Angeles.

A topographic map of the ocean-floor and some adjacent land along the coast of San Diego County, California, was prepared from the latest available data. The precise area mapped is between latitudes 32° 45' and 33°, and longitudes 117° 10' and 117° 20', and the contour-interval is 25 feet, the maximum difference in elevation being from 1750 feet below sea-level to 800 feet above. The scale is 4.05 inches per mile, or 1:15,625. Arrangements have been made for the Department of Geography of the University of California at Los Angeles to prepare a relief model from this map.

The following papers are in press: "Hydrographic sections and calculated currents in the Gulf of Alaska, 1929" by T. G. Thompson, G. F. McEwen, and Richard Van Cleve (Reprint No. 10, pp. 17-27); "The water-cycle between the ocean, atmosphere, and land," being published in the Proceedings of the United States Naval Institute.

The salinity- and temperature-data for the U.S.S. Hannibal cruises of 1933 were published in Hydrographic Office Publication 212. The samples collected in 1934 have been titrated for salinity, and both the salinity- and temperature-data have been tabulated, but these have not yet been sent to the Hydrographic Office. The samples collected in 1935 have been titrated for salinity, the temperature-records have been corrected, and the data have been tabulated. It is expected within the very near future to transmit to the Hydrographic Office the records for 1934 and 1935. A report incorporating the data obtained in 1933 was completed about a year ago and a report which will combine the results obtained in 1933, 1934, and 1935 has been almost completed by R. H. Fleming. Besides the salinity- and temperature-data, results of other chemical analyses of the water-samples will be included in the report. A considerable amount of work has also been done on the chemistry of the marine bottom-deposits.

Roger Revelle has completed a study of data and samples collected by U.S.S. Bushnell between Adak, Aleutian Islands, and Pearl Harbor, Hawaiian Islands, and a report is ready for transmission to the Hydrographic Office.

The data obtained from the southern California region, from off Lower California, and from the Central American region, both during the present year and during previous years, have been studied with a view of ascertaining the seasonal variations in the water-movements and the origin of the water-masses in these localities. Some of the results of this work, as well as of the chemical analyses listed below, will be reported to the International Association of Physical Oceanography at its Edinburgh meeting next September.

Chemical investigations--The scientific staff of the Chemistry Laboratory has consisted of E. G. Moberg, R. H. Fleming, and Katherine W. Gehring, as well as several Works Progress Administration workers. Advantage was taken of the assistance furnished by the Works Progress Administration to make a large number of chemical analyses both on water-samples collected during the current year and on water and other marine materials stored at the Institution for some time. The samples obtained during the past year are listed in Table 1. On all of the samples collected this year accurate salinity-determinations have been made and most of them have also been analyzed for calcium and titratable base. On most of the samples taken by the Scripps the oxygen-content, the pH, and the phosphate-content have also been determined. Nearly all of the 300 serial water-samples collected by Roger Revelle in 1934 between the Aleutian Islands and the Hawaiian Islands on board the U.S.S. Bushnell have been analyzed for calcium. (The salinity of all of these samples and the titratable base of many of them had previously been determined.)

As in previous years, surface- and bottom-samples from the Institution's Pier have been analyzed for salinity, pH, titratable base, phosphate, silicate, and, in some cases, for oxygen, calcium, and boron.

About 300 bottom-samples obtained from various depths by the Scripps in local waters and by the U.S.S. Hannibal in the Panama Region have been analyzed for their organic nitrogen-content, and through the courtesy of Dr. P. D. Trask many of these samples are now being analyzed for organic carbon by Dr. H. E. Hammar of the United States Geological Survey.

Because nitrogen does not enter into either chemical or biological reactions to any appreciable extent, oceanographers have recognized for some time that the atmospheric nitrogen-content of sea-water is a better index of the origin of the water than is the oxygen-content. The principal reason why the distribution of nitrogen has not been investigated is that there has been no satisfactory method for its determination. Consequently, experiments were made to determine nitrogen by means of the Van Slyke blood gas apparatus, and it is believed that a method has been devised that will prove practicable in laboratories on shore and possibly also on board ship.

Marine microbiology--Dr. Claude E. ZoBell has continued his studies on the measurement of the oxidation-reduction potentials of marine sediments and the influence of bacterial activity on the state of reduction of the sediments (Bull. Nat. Res. Council, No. 98. pp. 218-224, 1935). The oxidation-reduction potentials of strata from different depths as well as the vertical distribution of aerobes and anaerobes in mud cores has been published (Bull. Soc. Amer. Petrol. Geol., v. 20, pp. 258-269, 1936).

Assisted by D. Q. Anderson, the vertical distribution and relative abundance of bacteria in marine sediments which activate the following physiological processes of oceanographic significance have been estimated: Ammonification, proteolysis, nitrate-reduction, denitrification, nitrification, urea-fermentation, cellulose-decomposition, chitin-digestion, fat-hydrolysis, sulfate-reduction, starch-hydrolysis, and various hydrolytic processes. In collaboration with Dr. (Miss) B. Lloyd it has been found that bacterial activity as manifested by CO_2 evolution, NH_3 production, NO_3 reduction, and bacterial multiplication is greater in small than in large volumes of sea-water, this probably being a surface-phenomenon which may help to explain the distribution of bacteria in the sea. Miss W. Landon has been investigating the extent to which bacteria may serve as a source of food for mussels, copepods, and other marine animals. Mrs. C. Feltham has continued the work on the specificity of marine bacteria as indicated by the bactericidal action of sea-water on fresh-water species (Proc. Soc. Exper. Biol. Med., v. 34, pp. 113-116, 1936). In collaboration with Miss Helen Mathews air-masses of marine origin have been found to differ bacteriologically from those of terrigenous origin. Mrs. Alice Calloway is working on the osmotic pressure tolerance of marine versus fresh-water bacteria. An autochthonous bacterial flora in Great Salt Lake has been demonstrated by the direct microscopic procedure in collaboration with W. W. Smith of the University of Utah. Lake-water (salinity 36.23 o/oo) has been compared with sea-water as an environment for bacteria.

Phytoplankton--W. E. Allen has prepared a report, now in press, covering the most prominent results of the study of diatom-collections obtained by Roger Revelle on his mid-Pacific cruise on U.S.S. Bushnell in 1934. He has also made calculations and tabulations, and a considerable study of details has been completed to the end of the fourteenth year of daily collections of phytoplankton from piers at the Scripps Institution and at Pt. Hueneme, more than 100 miles farther north. Part of the microscope work has been done on the fifteenth year. A report covering certain general features in the studies of the first ten years is now in press. A taxonomic report on a study of diatoms from the Sea of Java prepared jointly by him and Dr. (Miss) E. E. Cupp has been published.

The experimental studies on "fouling organisms" carried on by W. E. Allen in cooperation with Dr. W. R. Coe of Yale University were closed in October 1935, at the end of the ninth year, and a report covering the major results of the work through the nine years has been submitted for publication in joint authorship.

Through the interest and cooperation of Templeton Crocker of San Francisco, a series of surface-catches of phytoplankton was obtained from the Gulf of California in November 1935 on a cruise of his yacht Zaca. A similar series of catches was made in the waters of Lower California by Captain Allan Hancock from his yacht Velero III in the spring of 1936.

Dr. E. E. Cupp has completed a paper entitled "Seasonal distribution and occurrence of marine diatoms and dinoflagellates at Scotch Cap, Alaska," which has been accepted for publication by the University of California Press. Particular attention has been given to centrifuge methods of phytoplankton analysis. A small number of samples collected from the Scripps Institution Pier, a short series of catches taken by Dr. McEwen in the Pt. Hueneme Region March 14, 1935, and the samples collected by the *Scripps* from June through September 1935 have been examined. Culture experiments with two species of the diatom genus *Nitzschia* have been completed and a paper, "Low concentrations of deuterium oxide and the growth of marine diatoms," with Dr. Fox and Dr. McEwen, has been completed and submitted for publication.

Foraminifera--M. L. Natland, although not a member of the staff of the Scripps Institution, has continued to work with the Institution in a study of the ecology of the living foraminifera in the Gulf of Catalina. T. W. Vaughan, in collaboration with W. S. Cole, temporarily at the Scripps Institution, and U. S. Armstrong, has completed several papers on fossil foraminifera, and others are nearly ready for press.

Zooplankton--A report by Martin W. Johnson on the seasonal migration of the wood borer *Limnoria lignorum* in northern waters has been published (Biol. Bull., v. 69, pp. 427-438, 1935). The investigation is being continued in San Diego Bay to determine the conditions in more southern waters. Dr. Johnson has completed a study of the developmental stages of the oceanic copepod *Eucalanus elongatus* var. *bungii*, including a northern and a southern variant, which has been accepted for publication. Additional study is being made of the status of the varieties of this species from collections taken at various points from Panama to the Arctic Ocean. Other work comprises a manuscript describing two new species of North Pacific copepods, ready to be submitted, and the descriptions of some hitherto unknown adult stages of other species completed; continuation of the study of zooplankton off the California coast with respect to its seasonal production, relation to the oxygen minimum layer, and to other environmental factors; culture experiments to determine the life-cycle and reproductive capacity, etc., of the littoral copepod *Thisbe*, and preliminary experiments on the effect of temperature on the rate of embryonic development and hatching of eggs of the pelagic copepod *Tortanus discaudatus*; the examination of a series of 100 plankton-samples taken by L. D. Phifer in the Bering Sea for production and distribution of larval invertebrates; and continued investigation of fouling organisms in the Institution's salt-water system.

Biology of fishes--Investigations by F. B. Sumner and his associates were as follows: (1) Continuation of investigation of relations between respiratory metabolism in fishes and susceptibility to certain anesthetics and lethal agents (in collaboration with N. A. Wells, later with Peter Doudoroff); (2) continuation of investigation upon influences of certain external stimuli on the accumulation of carotenoids in the tissues of fishes (in collaboration with D. L. Fox); (3) commencement of a quantitative study of melanin production in fishes, as influenced by varied conditions of background and incident light (in collaboration with P. Doudoroff); (4) commencement of a study of the intake and output of water and salts by euryhaline fishes, in sea-water and in various dilutions of this (P. Doudoroff). The last two lines of investigation have each required several months of preliminary experimentation with rather difficult technique.

Percy S. Barnhart has completed a monograph, "Marine fishes of southern California," illustrated by 292 figures (in press at the University of California Press).

Physiology--D. L. Fox has been investigating the metabolism of various carotenoid pigments in marine invertebrates and fishes, with reference to nutrition (independently, also with F. B. Sumner and with R. T. Young), and photic environment (with F. B. Sumner). Studies have been made of the influence of various concentrations of deuterium oxide (heavy water) upon different enzymes, especially some from marine animals (both independently and with Roderick Craig), also its effects upon the growth-rate of some marine diatoms (with Miss E. E. Cupp and G. F. McEwen). Investigation of the feeding and rate of water-filtration by the California mussel have been continued (with Roderick Craig and J. Rae Schwenck, visitors, summer 1935). Fox also collaborated with C. E. ZoBell and Miss W. A. Landon in an investigation concerned with the consumption of marine bacteria by the California mussel. G. W. Marks (resigned October 1) devoted much time to studies of catalase in marine animals and plants, and to comparative studies of the copper-content of a number of marine molluscs. Six or seven papers have been published, one is in press, and others are completed or in preparation.

Submarine geology--Dr. F. P. Shepard of the University of Illinois, working on the Institution's boat *Scripps* with members of the staff, dragged a large iron dredge with a bag of wire-netting up the walls of the submarine canyons around La Jolla and north of the Coronado Islands to obtain rock-samples. Rock-fragments were found in the dredge in all but one haul, showing that these walls are rocky. In some cases the dredge caught on ledges so hard as to stop the progress of the boat, but no great difficulty was experienced in getting it free. The rock obtained around the La Jolla and Scripps canyons consisted of shale and conglomerate which were clearly similar to the rock which outcrops in the cliffs north of the Institution. The conglomerate found on the steep walls of Scripps Canyon probably accounts for the steepness since the same type of conglomerate produces steep walls in a land-canyon in the north cliffs. The shale was full of holes made by the boring mollusc Pholas. Only one live form was found in the holes although numerous shells were present. The Eocene shales were traced to near the Cretaceous outcrops on the north side of La Jolla Head and appeared to indicate, in view of the south dip of the Cretaceous, that there was a fault on the sea-bottom separating the two series. This fault would be located to the south of the submarine valley which extends out from the Beach Club.

Dr. Shepard and Roger Revelle spent three days on the Coronado Islands, where they worked out the structural relations of the rock-formations on both the north and south islands, and made a brief reconnaissance of the middle islands. The rock obtained in the canyon north of the Coronado Islands consisted of sandstone and conglomerate, similar to deposits of probable Miocene or Pliocene age exposed on the south island.

Investigations on marine bottom-deposits have already been noted under "Chemical investigations" and "Microbiology" in this report. During the year Dr. E. M. Thorp completed a report entitled "The sediments of the Pearl and Hermes Reef," which was submitted for publication in the Journal of Sedimentary Petrology. In May 1935, he made an expedition to Great Salt Lake, Utah, to collect water-samples and oolites there. He received assistance from the Institution's chemical laboratory in the study of the chemistry of the water-samples. A report on his results has been nearly completed. Since Thorp is now the head of the Department of Geology at Baylor University, Waco, Texas, further reports on his work should be made to the Committee on Sedimentation of the Division of Geology and Geography, National Research Council.

Roger Revelle, in May 1935, submitted his report on the marine bottom-deposits collected in the Pacific by the Carnegie on its seventh cruise for publication by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. He has led in arranging additional chemical studies of marine bottom-deposits mentioned above.

During the past year additional studies have been made of littoral erosion and the shifting of sand on the sea-front of the Institution's property, as a contribution to a study of marine processes on the California coast.

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THE INFLUENCE OF THE MEDITERRANEAN OUTFLOW AT MID-DEPTHS IN THE SARGASSO SEA

Columbus Iselin

(Contribution No. 104 from the Woods Hole Oceanographic Institution)

It has been known for some time that in the eastern North Atlantic the salinity at mid-depths (500-2000) is often relatively high. There is no doubt among those who have examined the question that this is largely due to the outflow of water from the Mediterranean. Owing to the high rate of evaporation in the Mediterranean two currents are to be expected in the Straits of Gibraltar, namely, an inflow of Atlantic water at the surface and an outflow of relatively saline water along the bottom. Such currents have been frequently observed. The outflowing water leaves the Mediterranean with a salinity of about 38 o/oo, and according to Nielsen its volume averages 56,200 km^3 per year.

The salt that this current carries is absorbed into the Atlantic at mid-depths, for the Mediterranean water is relatively heavy and, after flowing across the shallow sill of the Straits, it sinks downward along the continental slope to about 1200 meters before spreading seaward. During its passage through the Straits and in the process of sinking, the original salinity of 38 o/oo is much reduced by mixing. Thus through turbulence enough normal Atlantic water is quickly absorbed into the Mediterranean outflow to reduce the salinity to a value of about 36.45 o/oo in the heart of layer at 1200 meters just off the Straits. While the amount of superficial Atlantic water which is thus drawn downward cannot be exactly calculated, for it is not known just where and at what depth the greater part of the mixing takes place, this admixture undoubtedly amounts to several times the volume of the pure Mediterranean water. Thus the so-called Mediterranean water in the North Atlantic is in reality largely superficial Atlantic water which has

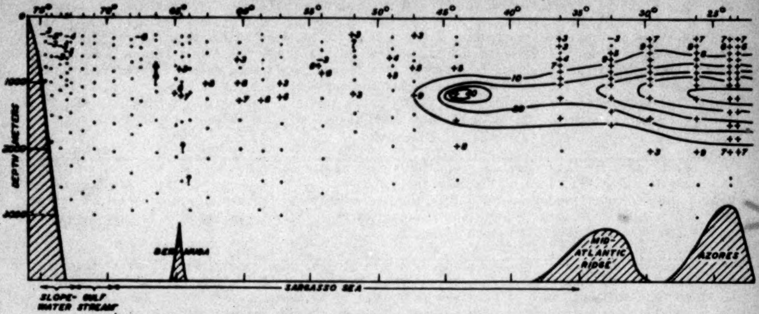


FIG. 1—SALINITY-ANOMALIES ON A SECTION RUNNING FROM THE EDGE OF THE CONTINENTAL SHELF OFF CHESAPEAKE BAY TO

been drawn into the vigorous downward mixing which takes place just off the Straits of Gibraltar.

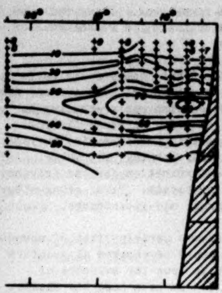
It was at first thought that, because of the effect of the Earth's rotation, the layer of maximum salinity at mid-depths must exert its main influence towards the north as it moves outward from its source. Indeed, the early observations seemed to support this view, because high salinities at 1200 meters were soon traced northward to the area southwest of Ireland. However, as more stations were made southward and westward from the Straits of Gibraltar, it became evident that the outflow of Mediterranean water was quite symmetrical.

In a recent paper by Wüst the full extent of the Mediterranean's influence in the Atlantic has been for the first time pointed out. In a series of most instructive charts this author has followed the main tongue, bearing a considerable admixture of Mediterranean water westward to mid-ocean. By a new method he has even shown that, from this layer of the North Atlantic, salt is supplied to the deep currents of the South Atlantic. It is now evident that the Mediterranean is largely responsible for one of the major differences between the waters of the Atlantic and the Pacific. Not only is the great depth of the isohaline of 35 o/oo in the Sargasso Sea thereby explained, but we can now much better understand the way in which saline water is brought to the deep layers of the Southern Hemisphere.

In studying the Atlantis stations from the Sargasso Sea, the influence of the Mediterranean water has been examined by the method of salinity-anomalies. Since this procedure has proved most instructive in the case of slow lateral movements at mid-depths, it may be of interest to briefly describe the procedure and to show some of the results arrived at in the case of the upper North Atlantic deep water, as Wüst has named the layer carrying Mediterranean characteristics.

In the preliminary examination of the data, it was found that many of the stations from the neighborhood of Bermuda gave identical temperature-salinity correlation-curves. However, at occasional stations one or more observations at mid-depths showed departures from the average conditions that were greater than could be accounted for by the observational error. Such departures can conveniently be recorded as the parts per hundred thousand in salinity by which the sample in question differs from water of the same temperature at the stations of the standard curve. Observations having salinities higher than given by the average curve were recorded as positive and those lower as negative. From these anomalies, sections were constructed of the various lines of Atlantis stations crossing the Sargasso Sea. In this way it was found that the small positive anomalies occasionally met with near Bermuda could be traced back to the Mediterranean outflow.

In the section of Figure 1 given as an example of the salinity-anomaly method, the stations run in a nearly straight line from the mouth of Chesapeake Bay on the west to Gibraltar on the east. The western half of the profile is based on Atlantis stations, while the eastern half comes from the results of various European expeditions. The anomalies at depths between 0 and 250 meters have not been plotted, as this layer is subject to seasonal changes, nor are any readings recorded from below 3000 meters. A small dot on this section indicates an observation that



THE STRAITS OF GIBRALTAR

does not differ from the standard curve by more than the error of the salinity-determination (±0.02 o/oo). Anomalies having values of between three and ten parts per hundred thousand have been recorded on the diagram. Those positive and greater than ten have been shown by a small +, the approximate values being indicated by the contour-lines. No negative anomalies greater than ten appear in this particular section.

An examination of Figure 1 shows in the west some small negative anomalies from the thermocline layer of the slope-water. This band, between the edge of the continental shelf and the Gulf Stream, is always slightly fresher for a given temperature than western Sargasso Sea water. Then near Bermuda at depths of between 800 and 1200 meters some small positive anomalies first appear. These can be clearly traced back to the much higher values of the so-called Mediterranean water in the eastern half of the ocean. It is also evident that in the central Sargasso Sea the positive anomalies are found at slightly shallower depths than those occupied by the main tongue of Mediterranean water. This is explained when we remember that the clockwise, superficial currents of the Sargasso Sea do not probably extend down to more than moderate depths. Therefore, positive anomalies are seldom carried westward from the under side of the wedge-shaped mass that gives anomalies greater than ten. Thus from the standpoint of the Sargasso Sea, the Mediterranean water exerts its greatest influence at moderate depths, the deeper positive anomalies being probably for the most part carried southward into the South Atlantic.

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CONTINUED EXPLORATION OF CALIFORNIA SUBMARINE CANYONS

Francis P. Shepard

Returning to California last summer the writer had the opportunity to continue work on the submarine canyons. Some of the results obtained appear to give new light on the general problem. These results are concerned with rather widely different phases of the work, and each phase will be discussed briefly in the following notes.

Rock from the canyon-walls--Attempts were made to obtain rock from the sides of the canyons. At first a tangle was employed with the hope of catching loose pieces of rock from the bottom. This proved very disappointing in its results. Later a large dredge with sharp cutting edges was constructed, following the system used by Stetson. This dredge was dragged up the sides of various canyons attached to a heavy cable. With this device remarkably good results were obtained both in work with the Scripps Institution near La Jolla and with the California Fish and Game boat at Monterey. In most places there was no trouble in encountering rock, nor in catching the rock by the cutting edge of the dredge. Nor was it, in general, difficult to break off the rock to get it to the surface. Several times the forward motion of the boat was suddenly stopped because of the strength of the rock encountered. However, gradual reeling in of the wire till the full lifting power of the waves was brought to bear on the boat led to the breaking off of the rock in all cases. This was even true with masses of granite of considerable size.

The rocks obtained were very diverse in character, varying from soft shales through substantial sandstones to the aforementioned granite. The age of the rock could be determined in a number of cases either by stratigraphic resemblance to rocks on the neighboring shores or through the fossils found in the rocks dredged. Rock-fragments from Coronados Canyon near San Diego were probably Pliocene. At La Jolla the rock could be assigned definitely to the Eocene by comparison with the nearby formations on land. Off Carmel, granite presumably of Jurassic age was encountered. On the sides of the Monterey Canyon, Late Pliocene or Pleistocene formations were obtained. These varied from unconsolidated material to well-cemented rock. Lithologically they ranged from impure limestone through shale to conglomerate and breccia. Dr. U. S. Grant IV examined the fauna which the material contained and identified several species. Of these Patinopecten caurinus (Gould) is indicative of Late Pliocene or Early Pleistocene age since it is found as a fossil in formations of that age in southern California. The others were not diagnostic except that they indicated the comparatively recent age of the formations. These included Cancellaria cooperi (Gabb), a recent species; Dendraster (Sp. indeterminate), a recent shallow-water species; and Saxicava arctica, a wide-ranging recent species.

The significance of these finds of rock on the walls of the California canyons are twofold. In the first place, it shows clearly that the canyons must have been cut out of rock and are certainly not non-depositional features kept open by currents while deposition was proceeding on either side as W. M. Davis suggested, nor could they be the result of muddy currents flowing down the continental slopes as was conceived by Daly as a possible origin for submarine canyons. Liquid-mud flows could have no power to cut into hard sandstones to say nothing of granite. Furthermore, the age of the rocks gives a basis for a minimum age-determination for the canyons. It shows that a number of them were either very late Tertiary or Pleistocene. Taken along with other data the probability is that the age was Pleistocene, very likely mid-Pleistocene.

Changing depth in canyon-heads--During previous work on the canyons certain lines of soundings had been run with great care to obtain accurate results which could be checked at a future date. In three places, lines were run again during the past summer to look for evidence of changes. This work was carried on off Newport, Carmel, and La Jolla. In each case the shallow water near the heads of the canyon was chosen as the best place for comparison. The results in each case indicate that there were changes. At Carmel the canyon was the same depth, but a little wider. At La Jolla there was some indication of greater depth, but at Newport the evidence of deepening was inescapable. Besides being deeper the channel was both wider and somewhat offset. The Newport Canyon was an ideal place for comparison since the Newport pier has been built out to the edge of the canyon which cuts diagonally across its end. Points on the pier were lined up with points on shore for the purpose of running the lines, and the same points were used in successive years. The results are shown in Figure 1. The sections indicate deepening during this interval with amounts of from 10 to 20 feet in many places. It is interesting to note that earlier soundings show that the deepening had probably occurred previously in the same channel, but of a smaller amount. The tendency for the channel to shift to the west is also evident. One cannot escape the conclusion that either mud-flows are carrying mud out of the canyon or that currents in the relatively shallow water perhaps combined with mud-flows are operating in this place. In view of the shallow water it is quite understandable that currents should exist here.

It is believed that the deepening observed in 1935 off Newport was due to the great waves which swept into the shore during certain periods of the preceding winter. These waves were of a mysterious origin since there was no storm on record either in the vicinity or out to sea. It is quite possible, however, that the storm occurred in some deserted part of the Pacific to the southwest of the area.

The northern San Andreas Fault--The writer had suspected previously that the San Andreas Fault could be traced seaward off the coast of Cape Mendocino. A large escarpment off that coast appeared to fit into the picture as the fault-trace. After the 1906 earthquake Mr. Matthes of the United States Geological Survey found traces of rifts at Shelter Cove which must have been formed at that time. This area was visited by the writer and the rifts were traced north to the

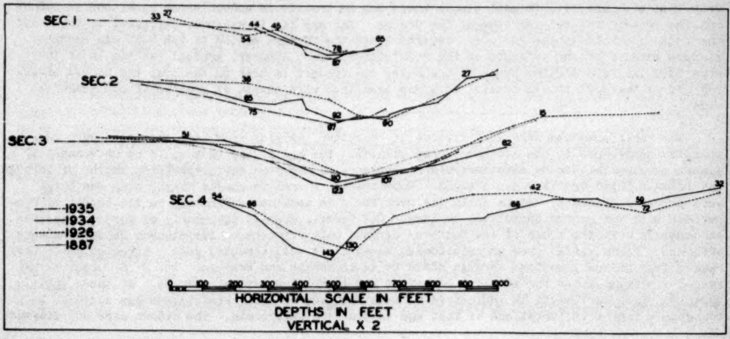

FIG. 1

coast. From there the Fault appeared to extend along the coast and evidence in the form of shear-zones were found for a number of miles in that direction.

It happens that five miles north of Shelter Cove a submarine canyon extends its head up practically to the coast. The coast inside this canyon was examined and it was found that there was no sign of a land valley. Instead the coast is very rugged, nor is there any valley within a half mile on either side of the place.

The explanation of the submarine canyon extending into an abrupt coast at this place may be found in the relation to the San Andreas Fault. This Fault is well known to have had large horizontal displacements. It seems probable that movement along this Fault has separated the submarine canyon from its landward connection. A possibility was discovered that there had been a movement of the order of three miles since the canyon was submerged.

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DREDGE-SAMPLES FROM THE SUBMARINE CANYONS BETWEEN THE HUDSON GORGE AND CHESAPEAKE BAY

H. C. Stetson

(Contribution No. 103 from the Woods Hole Oceanographic Institution)

In August, 1935, the research vessel Atlantis of the Woods Hole Oceanographic Institution made a dredging trip to the outer part of the Hudson Gorge, to two valleys cutting the continental margin off the Delaware coast between 30° 30' and 38° 06' north latitude, and to one off Maryland lying between 37° 30' and 37° 20' north latitude. With the exception of the outer gorge of the Hudson, these canyons are in every way similar to those described by Shepard from Georges Bank, and their general configuration is too familiar to everyone to warrant further description here (F. P. Shepard, Canyons off the New England coast, Amer. J. Sci., v. 27, pp. 24-36, 1934). In many places the slope of the walls is apparently above the angle of repose of unconsolidated material, and presumably cliffs of truncated strata form part of the canyon walls. It is not the purpose of this preliminary report to enter into a discussion of the origin of these features. We are only concerned here with the nature of the material found within the canyons themselves. Whatever their origin may have been, it is obvious that factors were once in operation the dating of which would be of importance to geologists. Last summer's reconnaissance was a continuation of the problem begun the preceding year on Georges Bank, namely, of attempting to fix the maximum age of these valleys by means of fossiliferous samples dredged from their walls and, secondly, of gaining some knowledge of the type of material of which the continental margin is composed.

Dredging operations are carried on in the following manner: The edge of a valley would be located by echo-soundings and buoy placed on it. The vessel would proceed slowly toward the middle of the valley until a steep cliff had been crossed. The course would be reversed and the dredge lowered and the depth recorded. The ship would then go ahead at about two knots laying out wire at the same speed to avoid kinking, the dredge meanwhile remaining stationary. Experience showed that about one mile of wire was necessary to assure a good angle of drag for this type of work at the depth at which the cliffs were found. The winch was then stopped and the vessel allowed to fetch up on the dredge and drag it up the face of the cliff. At times the dredge would anchor itself securely enough to check the vessel's headway. Tows were always made uphill and only the lower and upper limits could be recorded since the vessel was far ahead of the dredge. It is not possible, therefore, to fix the exact depth at which any single formation was encountered. The vertical range of each tow, however, was not great and in no case amounted to more than 300 meters.

It was anticipated from what we know of the structure of the Coastal Plain that the older formations found in the Georges Bank canyons would not be encountered in the canyons from the Hudson Gorge southwards, and such proved to be the case. The Coastal Plain formations constitute a wedge of nearly flat-lying sediments, with the thin edge at the Fall Line, dipping gently seaward and thickening as they go. They rest upon a beveled platform of igneous and metamorphic rock, itself with a seaward tilt, which physiographers term the Fall Line peneplain. The seaward dip of the beds averages from 40 to 50 feet per mile for the early Cretaceous formations to 10 to 15 feet per mile for the later Tertiary. At Atlantic City, New Jersey, well-borings have shown the top of the Miocene (Kirkwood) to be already 390 feet down, and at Wildwood, 300 feet (J. V. Lewis and H. B. Kümmel, The geology of New Jersey, Geol. Surv. N.J., Bull. 14, 1915). It is a matter of common observation that the continental shelf off this part of the Atlantic Coast is an extension of the Coastal Plain. If the same structural conditions as we know them on land hold reasonably constant for the seaward portion, and we have no reason for supposing that they do not, the upper parts of the canyons must necessarily be cut in very young strata. The steepest slopes of the valley-walls are apparently restricted to a zone about 200 to 800 meters below present sea-level. The depth at which these steep slopes are found below the top of the continental shelf is only a small portion of the depths of the canyons. Furthermore, at the continental margin there apparently is still a considerable thickness of sedimentary material below the valley-bottoms [Maurice Ewing and others, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part I--Methods and results, abstract Geol. Soc. Amer., Pr., 1935 (1936)]. Experience had shown in the case of the Georges Bank canyons that the only places where material could be obtained, which was not the product of present-day sedimentation, were in this zone of cliffs, likewise occurring at about the same depths. Elsewhere, because of lesser gradients, present-day accumulation has covered the older sediments with a mantle too thick to be penetrated by any sampling apparatus. This likewise was found to be the case in the southern canyons.

Let us now examine the different types of sediments which were found in the canyons. Twenty-three tows were made in all, thirteen of which yielded material very different from the sediment at present being deposited on the continental shelf and slope and in the valleys themselves. Fourteen cores were also taken with the explosion-type coring tube recently designed by C. S. Piggot. In the canyons at depths below 100 to 150 meters this modern sediment is a green, sandy silt becoming somewhat finer with increasing depth, but at the depths of water at which the tows were made the median diameter of the size-distribution ranges from about 0.06 to 0.1 mm. The sorting is poor because of the large admixture of sand. It is entirely unconsolidated and easily washed through the large mesh of the bag on the dredge. Smears of it, however, were almost always present when the dredge came on deck. It appeared in the top portions of nearly every core, and a great many of them chiefly from the valley-bottoms and gentler slopes were composed of it throughout. A few years ago two lines of bottom-samples were run by the Woods Hole Oceanographic Institution from the shore over the break in slope, the first one between the Hudson Gorge and the canyon immediately to the south, and the second falling by chance between the two southernmost canyons. These sediments from the top of the shelf were sands of varying degrees of coarseness, while those from the slope consisted of the same oozy green silt becoming finer with increasing depth.

The other materials found within the canyons are easily distinguishable from the foregoing by the degree of compaction and frequently by their texture. The material came up in angular chunks with freshly broken faces--pieces sufficiently hard in some cases to be nearly dry inside. In spite of the rough handling they received, worm-tubes and the burrows of various bottom-living organisms are preserved intact. Occasionally, seaweeds were found growing on some of the faces, showing that they were in direct contact with the water. No surface-deposits could ever attain the degree of compaction displayed here. In a tow from the southernmost valley the dredge came up full of fragments of a coarse-grained, highly indurated sandstone which unfortunately was unfossiliferous. These were obviously talus blocks, as they were weathered on all sides. The outcrop itself was never found. The most common are vari-colored clays, with median diameters ranging from about 0.002 to 0.001 mm and with poor sorting. Nowhere on the continental slope as far as is known do we find sediments at comparable depths approaching these clays in fineness of texture. It is not till much greater depths are reached, at stations well outside the continental margins, that similar median diameters are found. Occasionally silts were brought up having about the same values for median diameters and sorting as this unconsolidated green silt, which is the product of present-day sedimentation. These, however, are distinguished from the former by the compaction as noted above.

Dr. J. A. Cushman has examined the foraminifera from these compacted samples and states that they are all living forms, and that, though their exact geologic range is unknown, they can not be older than late Pleistocene. The living foraminifera of the unconsolidated green silt constitute a fauna easily distinguished from that of the compacted samples, and little duplication of species is found between the two.

As outlined above, the texture and compaction serve to differentiate sharply the samples just described from what is known to be the product of present-day deposition in this region. They must, therefore, be from an older formation, and they must have been laid down at a time when environmental conditions were very different from what they are today. It was to be expected that the upper parts of the canyon-walls would be cut in young material, but this does not necessarily imply Recent or even late Pleistocene.

In the case of the Georges Bank canyons, the narrowly restricted vertical range of the fossiliferous material, its relationships to deposits of glacial outwash and present-day silt, and the position of the Cretaceous-Tertiary contact support the assumption that it was obtained from truncated strata forming the actual walls, not from the fill of a preexisting cut (H. C. Stetson, Geology and paleontology of the Georges Bank canyons, Part I--Geology, Bull. Geol. Soc. Amer., v. 47, pp. 339-366, 1936). The youngest material obtained has been shown to be late Tertiary, probably dating from late Pliocene times (Joseph A. Cushman, Geology and paleontology of the Georges Bank canyons, Part IV--Cretaceous and late Tertiary Foraminifera, Bull. Geol. Soc. Amer., v. 47, pp. 413-440, 1936.

In the southern canyons the case is not so definite. The vertical range through which the material is found is greater, and there are no discernible contacts. Furthermore, though the evidence is strictly negative, it seems scarcely credible that the valleys could have been formed by either subaerial or submarine agencies since the deposition of material which is so youthful. MacClintock and Richards have recently placed in the Sangamon interglacial stage the widespread Gardiners formation of Long Island and southern New England, and the Cape May formation of New Jersey, both of which contain much clay (Paul MacClintock and Horace G. Richards, Correlation of late Pleistocene marine and glacial deposits of New Jersey and New York, Bull. Geol. Soc. Amer., v. 47, pp. 289-338, 1936. We are certain that the material under discussion is not the product of present-day sedimentation, but the strong possibility does exist that we may be dealing with the offshore component of Sangamon deposition which was laid down as fill in an older cut. Subsequent slumping and landsliding down the canyon-walls of stiff heavy clay of this sort would produce an irregular topography with many steep cliff-faces as is demonstrated in the case of Gay Head, Martha's Vineyard. If the material were thick enough, it could easily pile up at the base of any preexisting cliffs and effectively mantle the older formations below. The peculiar position of Georges Bank, which is separated from the mainland by the deep basin of the Gulf of Maine, may have prevented extensive deposition of this material in the canyons cutting its margin.

The study is not yet complete, but at the present writing we may draw the following conclusions:

(1) Material was dredged from the sides of the outer Hudson Gorge and from three canyons south of it, which is Recent and late Pleistocene, but which clearly is not the produce of present-day deposition.

(2) In contrast to the evidence previously obtained from the Georges Bank canyons, the dredged material may have come from the fill of an older cut and not from outcrops of truncated strata forming the actual walls.

(3) It is suggested that this material may be the offshore component of deposition which occurred during the Sangamon interglacial stage, and which resulted on land in the Gardiners formation of Long Island and southern New England and the Cape May formation of New Jersey.

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COMPUTATION OF THE TRANSPORT OF SURFACE-WATER DUE TO THE WIND-SYSTEM OVER THE NORTH ATLANTIC

R. B. Montgomery

(Contribution No. 105 from the Woods Hole Oceanographic Institution)

One of the most important forces which maintains the circulation of the ocean is that exerted directly on its surface by the wind. It is even assumed by some that the frictional force of the wind is the primary cause of most of the large-scale currents of the open ocean. Taking advantage of the recent improvements in the theoretical machinery necessary for computing the direct effects of the wind, I have attempted to compute one of these effects on a large scale, namely, the transports of the drift-currents resulting from the mean wind-distribution over the North Atlantic.

The general theory of ocean-currents by Ekman says that the effect of the wind is to produce a drift-current whose velocity decreases with depth according to a spiral, and which is essentially limited to the surface 50 or 100 meters. The unequal convergence of this current at different

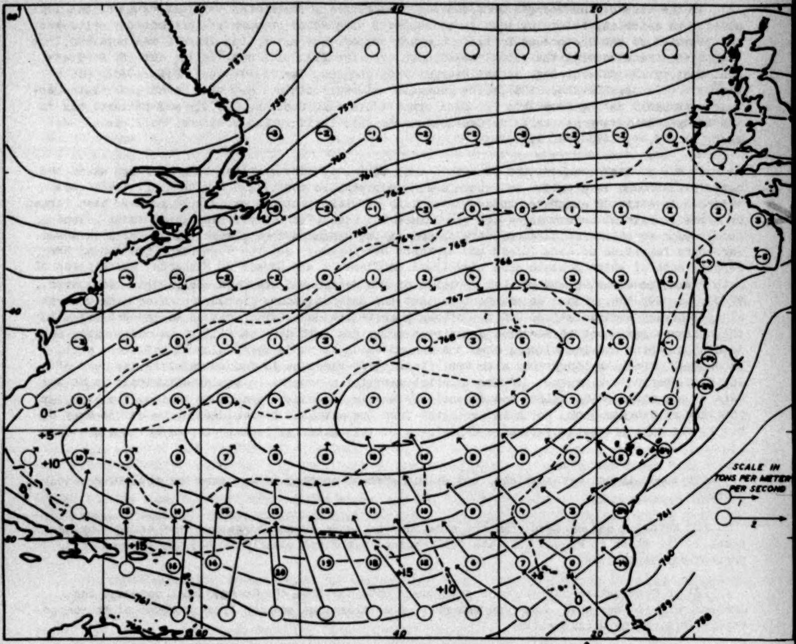

FIG. 1—SEA-LEVEL ISOBARS FOR JULY IN MM REDUCED TO LATITUDE 45°
[ARROWS SHOW TRANSPORT OF DRIFT-CURRENT IN METRIC TONS PER METER PER SECOND; NUMBERS IN CIRCLES ARE CONVERGENCE OF DRIFT-CURRENT IN CM PER DAY; BROKEN LINES ARE LINES OF EQUAL CONVERGENCE]

localities sets up pressure-gradients which result in gradient-currents. These would extend, in a homogeneous ocean, from surface to bottom, and there the bottom-currents would be superposed. We limit ourselves to the drift-current, which is the current contained in the surface frictional layer after the gradient-current has been subtracted.

Isolating this drift-current and treating it as a whole, it is seen that no friction is exerted on its lower boundary, and that the only forces acting on it are the wind-stress at the surface and the fictitious deflecting force. If the current has no acceleration, as we assume, then these forces must be equal and opposite; expressed for unit-area of the ocean this gives

$$\tau_0 = f\,T$$

where τ_0 = wind-stress, $f = 2\Omega \sin L$ = Coriolis' parameter, and T = transport of water in terms of mass per unit-time, per unit horizontal length normal to mean motion. The deflecting force acts $\pi/2$ *cum sole* from the mean motion, so the mean motion must be $\pi/2$ *cum sole* from the wind-stress.

The wind-stress in terms of the surface-wind is usually expressed by means of the non-dimensional constant γ, which depends on the height (z) at which the wind is measured and on the roughness of the surface, thus

$$\tau_0 = \rho\, \gamma^2 W^2$$

From theoretical considerations Rossby [see 1 of "References" at end of paper] has concluded that γ depends on z, and on a certain roughness parameter z_0, in the following manner

$$\gamma = k_0/\ln[(z + z_0)/z_0] \qquad k_0 = 0.38$$

This relation seems to be verified by experience for steady winds greater than about three to five meters per second. Below this critical wind speed γ probably drops to about one-half, but above this speed z_0 and γ seem to be remarkably constant. The determinations of z_0 given in Table 1 have been made by Rossby [2] on the basis of the available observations.

Table 1

Source of data	Method	z_0 in cm	U_g in mps
Ekman	Storage of water	0.75	about 20
Wüst	Velocity-gradient near surface	0.6	about 10
Jeffreys	Angle between surface-wind and gradient-wind	0.70	10.25
		0.49	15.25
		0.32	about 22
Jeffreys	Ratio between surface-wind and gradient-wind	0.85	10.25
		0.36	15.25
		0.64	about 22

Remembering that γ changes slowly with z_0, these values are remarkably uniform. The only other indications of the values of γ and z_0 are that by Sutcliffe which is much smaller, and that by Sverdrup which is much larger. The values from these latter authors are less reliable than those from Wüst and Jeffreys, so it is justifiable to use $z_0 = 0.6$ cm for steady, moderate and strong winds, consistent with Table 1 above. Due to the uncertainty of the value of the critical wind-speed, I have used $z_0 = 0.6$ cm also for light winds, bearing in mind that the resulting estimates of the drift are probably too large.

In the present case the wind-system employed is that of the gradient-wind computed from the mean pressure-distribution for the month of July. I have used Defant's [3] mean pressures, which are given for the intersections of each five degrees of latitude and longitude. His pressures are the means of the pressures read off at the five-degree intersections by interpolation from the isobars on daily synoptic maps for the period 1881 to 1905.

The direction and magnitude of the surface-stress have been computed by means of theoretical relations derived from similarity considerations by Rossby [1]. If φ_s is the angle between the gradient-wind and the surface-wind (or surface-stress), U_g is the gradient wind-speed, and k is a universal constant which has been found to be about 0.065, then

$$N \equiv U_g/f\ z_0 = [2\sqrt{2}\ k_0/9\ k^3 \sin \varphi_s]\ e^{[2k_0(\cot \varphi_s \quad \sqrt{0.5})/3k]}$$

and

$$\tau_0 = (9k^2/4)\,\rho\,U_g^2 \sin^2 \varphi_s$$

By means of the first of these equations φ_s may be computed from N, and from the second the net transport of the drift-current is found

$$T = (9k^2/4)\ (\rho/f)\ U_g^2 \sin^2 \varphi_s$$

It is impossible to give here even a brief summary of Rossby's theory. Its general significance may be indicated, however, by stating the distribution of eddy-viscosity which it implies. In the original theories by Ekman and by Taylor for the distribution of wind within the layer of frictional influence, eddy-viscosity was assumed to be constant in the vertical direction. This has been extended by various authors to the case of an eddy-viscosity varying according to simple power laws, but the absolute value remains arbitrary. Rossby's theory, however, definitely defines the eddy-viscosity distribution in terms of the external parameters. He divides the region of frictional influence into two layers, a surface-layer of thickness H and an upper layer of thickness h. It is found that H = 0.12 h. At the surface the eddy-viscosity has a finite value of $\rho\ k_0\ z_0\sqrt{\tau_0/\rho}$. It increases linearly within the layer H, where the stress is assumed constant, according to

$$\eta = \rho\ k_0\ (z + z_0)\sqrt{\tau_0/\rho}$$

reaching at the top of the layer a maximum value of

$$\eta_{max} = \rho k_0 H\sqrt{\tau_0/\rho} = \rho f h^2/3\sqrt{2} = (27k^4/4\sqrt{2})\,(\rho U_g^2/f)\sin^2\varphi_s$$

Within the layer h the stress decreases upward since the volume-forces (pressure-gradient and deflecting force) are taken into account, and the eddy-viscosity decreases to zero at the top according to

$$\eta = (\rho f/3\sqrt{2})\,(h + H - z)^2$$

Thus the eddy-viscosity is everywhere defined in terms of U_g, f, and z_0.

On the chart of Figure 1 are shown the pressure-distribution and, by means of arrows, the transport at the center of each five-degree square. From the transport-vectors have been computed the convergence in each five-degree square, which is indicated by the number within the circle, expressed in cm per day. Lines of equal convergence are drawn for 0, 5, 10, and 15 cm per day.

In carrying through this computation it has been necessary to make use of assumptions which may have introduced considerable error. The basic assumption is that the mean of the instantaneous transports is the same as the transport computed from the mean pressure-distribution. The correctness of this assumption becomes doubtful when we remember that the deviations from the mean (pressure-gradient, for instance) are greater than the mean itself, which may be seen by the fact that the synoptic map often shows no resemblance to the mean map. Since the gradient-wind and the pressure-gradient become quickly adjusted, and since there is a linear relation between the two, there is no reason to doubt that the mean air-movement at the gradient wind-level is given approximately by the mean pressure-distribution. But between the gradient-wind and the surface-stress there is not a linear relation. It would be possible to use as the mean surface-stress the mean computed from synoptic maps for a given period, but this lengthy computation has not yet been attempted. Further, the adjustment between surface-stress and transport of water is far from instantaneous, and, whether the time-mean of the relation between the two for the unsteady state is exactly the same as the relation for the steady state, is subject to doubt. These considerations give greater uncertainty in the region of prevailing westerlies, where the wind is more unsteady, but where, however, the transport is much less. In the trade-wind region the winds are much more steady.

In computing the surface-stress from the gradient-wind the validity of Rossby's theory has been assumed. This is unquestionably the most useful theory for work of this kind that has appeared, but the full extent to which its applicability extends has not yet been verified by experience. It must also be borne in mind that these equations represent conditions in an adiabatic atmosphere; if there is stratification within the normal height of frictional influence, the actual surface-stress is less than the computed one. Furthermore, the value of the constant k is not known accurately, or that of z_0 as mentioned above.

A difficult question always arises when calculations of this kind are carried near the equator. At a distance from the equator the sum of forces due to pressure-gradient, friction, and deflecting force is zero for the steady state. In computing transport of water (or gradient-wind) we assume no shearing stress on the bottom of the drift-current (complete absence of shearing stress). On nearing the equator with a finite surface-stress (pressure-gradient) the transport (gradient-wind) becomes larger and larger. At the equator itself there is no deflecting force, so here there must be a shearing stress at the bottom of the current to balance a finite surface stress. [Another possibility would be that the surface-stress is balanced by accelerations, but, since the whole drift-current is essentially a frictional phenomenon, this seems much less likely.] Obviously, then, this shearing stress must also be effective over a finite region near the equator. But how far from the equator does this effect extend? In particular, does it extend as far as the calculations of transport at 12°.5 north?

The theoretical depth of the drift-current becomes rapidly deeper on approaching the equator. It seems reasonable to assume that the shearing stress at the bottom of the current becomes important where this depth becomes unreasonably great. At 12°.5 the computed gradient-wind is about 9 meters per second, so the surface-stress may be found from $N = U_g/f\,z_0 = 4.8 \times 10^7$, $\varphi_s = 16°.6$, and $\sqrt{\tau_0/\rho} = (3/2)\,k\,U_g \sin\varphi_s = 25$. The major part of the depth of the drift-current is [1]

$$h = (3k/f)\sqrt{\tau_0/\rho_w} = (3k/f)\sqrt{\rho/\rho_w}\sqrt{\tau_0/\rho} = 5300 \text{ cm} = 53 \text{ meters}$$

This is a reasonable value, and throws no doubt on the values of transport found at this latitude.

Although these considerations indicate that the calculated values of the transport should not be relied upon in too great detail, it is reasonable to assume that the order of magnitude is correct. The values of convergence depend on differences of transport; but here again the total over a large region should be of the correct order of magnitude, though the position of the maximum convergence may easily be shifted somewhat.

Unfortunately it would be very difficult to verify the computed values of transport by direct observation, since the drift-current is superimposed on other currents which are often much stronger. It would, however, be possible to obtain observations which would check some of the steps necessary in making the computation. For instance, the surface-stress in terms of the surface-wind could be studied very nicely from further observations of the wind-gradient within the 10 or 20 meters directly above the ocean-surface.

It is not my purpose to discuss here the significance of the results obtained, but there are a few remarks which should be made.

If we add all the convergences within the region bounded by the line of zero-convergence and by 20° north, we get 9.7 million tons per second. Or, if we add to this the 3.9 found between 15° and 20°, which is more doubtful, we get 13.6 million tons per second.

The total northward transport across the parallel of 15° north between Africa and 65° west is found to be 8.9 million tons per second, and that across 20° north between Africa and 70° west is 5.97 million tons per second.

The divergence from the African coast is roughly the outward transport across the following line: Starting from off the Portuguese coast at 40° north and 10° west, south to 30° north, west to 15° west, south to 25° north, west to 20° west, south to 15° north, and finally east to the African coast; the net transport is 1.8 million tons per second.

In order to obtain an idea of the significance of the order of magnitude of these quantities, they may be compared with the transport of the Gulf Stream off Cape Hatteras, which is normally between 80 and 90 million tons per second.

Perhaps the most striking consequence of this study is that the region of maximum convergence is not within the Azores high-pressure area, but is some distance to the southwest. In fact, according to this calculation it is displaced more than a thousand miles. Unfortunately its exact location, even according to the methods here used, cannot be given because Defant's pressure-values extend southward to only 10° north.

This brings up a matter which I would like to emphasize. To my knowledge, these values from Defant are the only ones of a similar character which cover a large ocean-region. The very elaborate atlases of the Koninklijk Nederlandsch-Meteorologisch Instituut give, for each degree square, the mean of pressures observed by ships within that square for each of the twelve months. For a study of this kind they turn out to be of very little value. If studies of this kind should prove to be of value, it will be indispensable to have available detailed mean values of pressure and wind-roses over as much of the ocean-regions as possible, which have been obtained by interpolation from synoptic maps, such as those of Defant and Clayton [4]. If this type of study should have any bearing on the field of long-range weather-forecasting, then mean values should also be available for short periods, such as individual months. For North America, it would seem that the Pacific Ocean would be fully as important as the Atlantic.

Note: This computation is presented in greater detail in the paper by R. B. Montgomery on Transport of surface-water due to the wind-system over the North Atlantic, published in Papers in Physical Oceanography and Meteorology, v. 4, No. 3, 1936.

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OCEANOGRAPHY IN BRITISH COLUMBIA IN 1935

C. McLean Fraser

The work in oceanography in British Columbia during 1935 was largely centered in the activities of the Biological Board of Canada at the two main stations, Nanaimo and Prince Rupert, and several subsidiary field-stations for carrying on special investigations. Cooperating with the Biological Board and contributing to these activities, the University of British Columbia, the Hydrographic Service, the Meteorological Service of Canada, and the Naval Service of Canada may be specifically mentioned. There were 18 members of the regular staff of the Board and 12 voluntary workers during the year. Outside of the Province, several others have contributed by working on material or data supplied from this coast. During the year 68 papers were published.

The nature of the researches may be considered by treating them under the four heads: (1) Physical and chemical oceanography; (2) fundamental biology; (3) fisheries; (4) fisheries technology.

Physical and chemical oceanography--The area under hydrographic and hydrodynamic examination was extended to include the west coast of Queen Charlotte Islands. The Hydrographic Service of Canada continued work on the west coast of Vancouver Island, but the major portion of the work, that done by the C.G.S. Wm. J. Stewart, was largely confined to the coast of the Queen Charlottes. The whole Kunghit Island Area, Houston Stewart Channel, the west coast of Moresby Island, the western portion of Skidegate Channel and the southern portion of the west coast of Graham Island, and nine of the larger bays in this Area, were surveyed. Opportunity was afforded to make observations, obtain water-samples and plankton-collections, and these were treated in much the same way as were the collections from the west coast of Vancouver Island in the previous year. In connection with colorimetric analysis of sea-water for determination of the amount of the various nutrient salts, a photoelectric colorimeter was devised.

In addition to the physical and chemical records of conditions in the inner waters, particularly of the Strait of Georgia Area, observations are now recorded at five outlying light-stations, namely, in Barkley Sound, in Nootka Sound, in Quatsino Sound, in Queen Charlotte Sound, and in the Prince Rupert Area. These are being used to prepare continuous charts for several years to show the hydrospheric and atmospheric conditions along the Canadian Pacific Coast, their geographical, daily, seasonal, and annual variations, and their interrelations, with a view of determining the meteorological factors that affect the movements of the various commercial fishes. The observations of temperature, chlorinity, and hydrogen-ion concentration are made in greater detail at Prince Rupert than in any of the other areas.

Fundamental biology--In connection with the work on the Wm. J. Stewart off the coast of the Queen Charlotte Islands, opportunity was afforded to make representative, littoral, zoological collections throughout the area covered by the survey, so that much information was obtained concerning the fauna in an area hitherto unexplored. A limited number of hauls made by tow-net and dredge gave some indication of the nature of the fauna in the adjacent waters. In both cases, material additions were made to distribution records.

Further attention has been given to the incidence of boring and sessile organisms, more especially Bankia and Limnoria, on wooden structures in British Columbia waters, with special reference to seasonal settlement and seasonal intensity of attack.

Culture-methods for rearing crabs and hermit-crabs through the larval stages have been worked out in detail and the first larval stages of several species have been described.

In the oyster investigation, attention has been centered on the Japanese oyster, Ostrea gigas. Much has been done towards discovering a means of counteracting the uncertainty of reproduction of this species in Canadian waters. Spawning induced by the dissemination of gonad material at high tide over the oyster-beds has, in some cases at least, been followed by a heavy settlement of young oysters.

From a physiological point of view, it has been ascertained that, in this species, circulation of measurable quantities of water can take place at temperatures almost as low as 0° C. This ability to circulate water and collect food at such low temperatures probably accounts for the continuous growth of this species throughout the winter in British Columbia waters.

Reproduction in the two species of commercial clams, Saxidomus giganteus and Paphia staminea, has been studied in greater detail, with special reference to time of spawning and the appearance of the various larval stages.

Faunistic and distributional studies have been continued, more particularly with fishes, molluscs, polychaetes, and hydroids.

The stomach contents of fur seals and of water-fowl (the merganser ducks in greatest detail) were examined to get some information concerning the economic relation of these species to other marine organisms, with commercially valuable fishes much in mind. Following this matter up, it was discovered that the stomach contents of the sculpin, Cottus asper, commonly contained the remains of young salmon, but the sculpin is a main item of diet of the merganser duck.

Fisheries--The study of the annual samplings of the sockeye salmon run to Fraser, Skeena and Naas rivers, and Rivers Inlet was made as usual.

From a ten-year study of the efficiency of propagation, natural and artificial, of sockeye salmon at Cultus Lake, British Columbia, it was found that roughly 95 per cent of the released fry perished during the first year's residence in the Lake. An investigation has been begun to determine to what extent predatory fishes contribute to this loss, and how far the mortality may be reduced by destroying predators.

Certain minor questions regarding the Pacific salmons were cleared up, for example, variation in certain meristic characters, identification of the young of the five species, the relation of body-length to number of eggs in the female, re-utilization of sockeye-salmon milt, variation in size of sockeye-eggs during development.

An analysis of the pilchard fishery of 1935, biologically and statistically, made a comparison with previous years possible. In order to learn something of the migration-habits of the pilchard, experimental tagging was carried out successfully, and a large-scale tagging experiment is proposed. The tagging is done by inserting nickel-plated iron tags in the abdominal cavity of the fish, with the expectation of recovery by the use of magnets placed in suitable places in reduction-plant machinery.

Scale-reading in pilchards has not yet been done satisfactorily, but age-determination by otolith examination has given good results.

Catch-statistics of the herring fisheries for the season 1934-35 were analyzed. Extensive counts and measurements that were made, taken into consideration with data previously obtained, show conclusively that there are several racial populations in the Vancouver Island Area. A study of the age composition of herring from Barkley Sound, taken in the earlier years of the fishery, indicates the presence of dominant year classes. The selectivity of herring drift-nets of mesh of different sizes was determined.

The possibility of successfully planting shad on the west coast of Vancouver Island was investigated. Vertebral counts in capelin showed a difference in the mean vertebra number in the male and female. Further information has been obtained on growth in the early stages of the ling cod.

The fishes collected off the west coast of Vancouver Island in 1934 and off the coast of the Queen Charlotte Islands in 1935 were classified. Several new distribution-records were obtained, including some that were reported for the first time in Canadian waters.

Fisheries technology: Fish-oils--Satisfactory accelerated weathering tests for pilchard-oil paint-films were developed. Further investigation has been carried out on the production of durable varnish or enamel by the steam-distillation of pilchard-oil at a high temperature. The production and storage of pilchard-oil and standardization of its vitamin qualities for feeding purposes are still to the fore. Recommendations have been made for the cleansing of drums intended for pilchard-oil storage.

In connection with the industrial development of a method of separating vitamin-potent liver-oils, an investigation of chemical means of preserving fish-livers as much as possible from bacterial and autolytic action, while en route from source of supply to point of oil-production, has been undertaken.

Attempts to find out the reason for non-correlation of physical, chemical, and biological assays for vitamin-content of pilchard-oil are being continued. Clinical tests on "Thalattols" (medicinal oils) were conducted during the year.

Investigation of the properties of the unsaturated fatty acids (and their esters), found in fish-oils, to get a better understanding of the mechanisms underlying the reactions involved in the processing of such oils for various industrial uses, was concluded. These studies included: Study of iodine-value methods; action of ultra-violet light; isomerism; molecular weight; viscosity and refractive-index determination of polymerized oils in various solvents.

Bacteriology--The industry is gradually adopting methods recommended for disinfection in the handling of fresh fish. The possibility of developing an "antiseptic" ice for packing fresh fish is being investigated. New and better ice-glazes for frozen fish have been obtained. Scientific proof has been obtained that the low temperatures for optimum death-rate of bacterial populations do not coincide with those for optimum protection of fish or animal tissue against denaturation. Various difficulties experienced in canning shrimps, crabs, and clams have been overcome. An investigation into the nature of wood-rot aboard ship has been started.

Refrigeration and engineering--Much of the work in refrigeration and engineering has been done in cooperation with the work in chemistry and bacteriology, to which reference has already been made.

Curves have been made to show the velocities in various cooling and freezing methods.

Papers have been published, or are ready for publication, to embody the results obtained in nearly all of these various investigations.

[Note: Much of the information for this report was obtained from the annual report of the Nanaimo Station by the Director, Dr. W. A. Clemens, and of the Prince Rupert Station by the Director, Dr. N. M. Carter.]

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THE WATERS OF THE PACIFIC BEYOND THE CONTINENTAL SHELF OFF THE COAST OF WASHINGTON, OREGON, AND NORTHERN CALIFORNIA

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The manuscript for this paper was not submitted.

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AMERICAN GEOPHYSICAL UNION

Seventeenth Annual Meeting

SECTION OF VOLCANOLOGY

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VOLCANOLOGICAL BORON COMPOUNDS

Waldemar T. Schaller
(Published with the approval of the Director, U. S. Geological Survey)

I wish to present what evidence we have as to the geochemistry of boron minerals as related to volcanological processes, or, in other words, what are the volcanological boron compounds?

Volcanological processes, considered only as they apply to this question, may be grouped for present convenience as follows: (1) Extrusion of volcanic rocks; (2) volcanic exhalations including fumaroles and solfataras; (3) hot springs.

(1) Extrusion of volcanic rock--I know of no boron mineral which is a primary constituent of volcanic rocks, in the sense that the olivines, pyroxenes, and feldspars are such primary constituents. Boron compounds accompany volcanic eruptions and extrusions but are not fixed in the primary minerals of the volcanic rocks.

I agree fully with Foshag that the original source of the boron, now generally fixed as lime and soda borates, is most probably to be found in the hot springs and solfataras connected with volcanic activity. But the boron minerals in which the boron is fixed and as now found are later than the formation of the volcanic rock itself.

(2) Volcanic exhalations--These are essentially vapors. The only boron minerals known to be of direct volcanic-exhalation origin, that is, to have been brought up in a vapor form, are five, namely: Sassolite, boric acid, H_3BO_3; larderellite and ammonioborite, two hydrous ammonium borates, probably $(NH_4)_2O.5B_2O_3.5H_2O$; avogadrite and ferruccite, two alkali boro-fluorides, the first KBF_4 and the second $NaBF_4$.

Boric acid and the ammonium borates are volatile in steam. The two boro-fluorides have only recently been described as volcanic sublimates from Vesuvius and apparently are very scarce. There is no authentic record of the occurrence of any sodium borate as a direct volcanic-exhalation product, either as a volcanic sublimate or as a fumarolic or solfataric deposit. A reported sodium borate from the solfataric region in Tuscany, Italy, has been found on later study to have been erroneously determined, as the material contained no sodium.

Borates of soda and of lime could probably form, by solfataric vapors, bringing up boric acid, ammonium borates, or possibly boro-fluorides, reacting with already formed soda or lime minerals to produce soda or lime borates. But the soda and lime borates were not brought up as such by solfataric vapors.

Several theories have been advanced as to the chemical combinations in which boron is transported as a vapor. These include such compounds as boron nitride, boron sulphide, boron hydride, and boron fluoride. While such speculations are very intriguing and possibly of real geochemical value, they still must be regarded only as speculations.

Sassolite or boric acid is probably the commonest volcanic-exhalation boron compound. It occurs in Italy at the solfataric region of Tuscany, at Pozzuoli (just north of Naples), at Vesuvius, and on the island of Volcano, one of the Lipari islands, north of Sicily. A. W. Grabau (Geology of the non-metallic mineral deposits other than silicates, v. 1, p. 38, 1920) gives as additional localities the fumaroles of California, Nevada, Caucasus, etc.

Sassolite is not a conspicuous mineral and may have been overlooked at other localities. E. T. Allen and A. L. Day (Hot springs of the Yellowstone National Park, Carnegie Institution of Washington, Publ. No. 466, p. 122, 1935), in their Yellowstone report, state that boric acid may be collected with the steam from the bored wells of California, but I could not find any mention of the occurrence of sassolite as a mineral in their report on the California geysers (Steam wells and other thermal activity at "The Geysers" California, Carnegie Institution of Washington, Publ. No. 378, 1927). Similarly boric acid was found in all the incrustations analyzed from the Valley of Ten Thousand Smokes (E. G. Zies, The Valley of Ten Thousand Smokes, Nat. Geog. Soc., Contributed Technical Papers, v. 1, No. 4, p. 41, 1929), but it was not reported as occurring as the definite mineral, sassolite.

In the development of many metamorphic rocks, boron, in some combination, brought up either as vapor or in solution, has reacted with the constituents of the rocks through which it passed and has formed a long series of minerals (about 60 minerals containing boron are known)--anhydrous borates of alumina, iron, magnesia, lime, tin, titanium, and others--hydrous borates of all these elements except aluminum and titanium but including beryllium, manganese, phosphorus, and arsenic, and the long list of 20 boro-silicates.

The most probable combination of the boron is that of boric acid, but as eight of the 60 boron minerals contain fluorine (which has not been looked for in many of the other boron minerals) it may be that some fluo-boron compound was of equal importance. Such metamorphic processes, however, are not of volcanological character, as here defined, but are mentioned to emphasize the importance of boron as a factor in many rock-forming processes.

(3) Hot springs--Boron is a common constituent of hot springs. As far as known, the only boron compounds formed directly as a mineral by the evaporation of the hot-spring waters are borax and sassolite. Boric acid and carbonate of soda, also a common constituent of hot springs, readily react to form sodium borate. Sodium carbonate is usually present in hot springs in much greater quantity than boric acid, so there is little chance for boric acid to remain uncombined. The evaporation-products of hot springs, containing borax, usually contain abundant sodium carbonate crystallized out as trona and other carbonates, indicating an excess of sodium carbonate over boric acid.

Borate of soda occurs, along with sodium chloride and sodium carbonate, as efflorescences on the dried mud streams ejected from the mud volcanoes in the Kertch peninsula in southern Russia (W. S. Vernadsky and S. P. Popoff, Ueber den Boraxgehalt von Eruptionsproducten aus dem Salsengebiet von Kertsch und Taman, Zeitschr. prakt. geol., v. 10, pp. 79-81, 1902). It was also found in solution in the waters of the associated crater-pools. This occurrence would seem to represent mud volcanoes or hot mud springs rather than volcanic exhalations.

Boric acid and sulphur were reported (Hermann v. Schlagintweit, Ueber das Auftreten von Bor-Verbindungen in Tibet, SitzBer. math.-phys. Cl., k. b. Akad. Wissenschaften München, v. 8, p. 527, 1878) as occurring in abundance mixed with borax in the hot-spring deposits of West Tibet. Smaller quantities of sodium chloride, ammonium chloride, magnesium sulphate, and alum are also present. Grabau (op. cit., p. 38) also gives the hot springs of Chile as an occurrence of sassolite.

All hot-spring deposits containing borax, as recorded in the literature, contain other saline minerals in abundance. These are chiefly the carbonates, chlorides, and sulphates of soda and lime. Sulphates of magnesium and of aluminum are also abundant in places.

In conclusion, then, the recorded evidence indicates that the only volcanological compounds of boron, found as minerals, are: (1) Those formed by volcanic exhalations (including fumaroles and solfataras), namely, boric acid, ammonium borates, and alkali boro-fluorides, and (2) those formed from hot springs, namely, boric acid and sodium borate.

U. S. Geological Survey,
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THE ORIGIN OF LAMPROPHYRES

G. F. Loughlin

Abstract--A preliminary suggestion that lamprophyres may be of hydrothermal origin.

U. S. Geological Survey,
Washington, D. C.

A SOURCE OF HEAT-ENERGY IN CRYSTALLIZATION OF GRANODIORITE MAGMA, AND SOME RELATED PROBLEMS OF VOLCANISM

W. S. Burbank

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Introduction

Evidence obtained from thin sections, polished sections, and chemical analyses of granodiorite porphyries from the Ouray District of Colorado show that during crystallization of the granodiorite magma a number of shifts occurred in the equilibrium between the oxides of iron. These changes are reflected in processes of mineralization associated with the magma. The geologic setting of the igneous bodies and episodes of fissuring connected with the mineralization indicate that relief of pressure was the primary cause of the shifts in equilibrium. The iron occurring in the crystallized products and in the residual magmatic liquids is changed from its low to its high state of oxidation and thus provides an internal and potential source of heat-energy in crystallizing magmas. The transformation of the potential energy into heat is shown to occur both as an episodic process, interrupting the normal course of igneous metamorphism and mineralization near the magma bodies, and also as a more or less continuous process in the production of primary subalkaline magmas. The energy-transformation is so controlled by crystal fractionation within the magma-hood that it provides a mechanism by which magma bodies are enabled to rise in the Earth's crust by selective fusion of salic material.

The phenomena appear significant in relation to the problem of how metalliferous concentration takes place in magma bodies, and with regard to the manner in which materials are transported from the magma to the surrounding rocks. In veins and replacement-deposits near the Ouray granodiorite certain silicate and sulphide molecules appear to have been transported in a single-phase medium which was identical with the residual fraction in the pores of the crystallizing magma. During episodes in which relief of pressure occurred, however, a gas-phase appears to have existed in addition to the liquid fraction. During and following the appearance of the gas-phase additional substances concentrated by the resulting oxidation are distilled from the magma-hood to the surrounding rocks.

Certain deductions regarding the mechanism of crystallizing igneous bodies, based upon the established processes, permit some theoretical applications to processes of volcanism and to the production of normal subalkaline magmas and their differentiates. A quantitative estimate of the available heat-energy in an example of igneous differentiation is appended.

Geologic setting

The granodiorite porphyry bodies of the Ouray District are chiefly laccoliths and sills, which cover a roughly elliptical area at least five miles in longest diameter. The intrusions are of late Cretaceous or early Eocene age. The largest injections of magma occurred at the base of the Mancos shale of Upper Cretaceous age, but thin sills and dikes intrude the underlying Mesozoic and Paleozoic sedimentary rocks. The larger laccolithic bodies originally exceeded 1500 feet (457 m) in thickness, but were somewhat reduced in thickness by early Tertiary erosion. At the time of the igneous intrusions the overlying cover of Upper Cretaceous formations, including possibly the older Eocene beds, had a thickness estimated to be from 2 to 3.5 km. Most of the exposed mineralized rock, however, lies in the underlying sedimentary beds, from a few meters to 500 meters below the base of the laccoliths. The principal channel through which the concordant injections were fed is believed to be exposed near the town of Ouray, and is somewhat eccentric with respect to the area covered by the laccolithic bodies. Where exposed, the channel has a maximum width of about 600 meters and a length of about 1200 meters. Because of the small size of this channel and the relatively impervious nature of the sedimentary formations the metamorphism caused by emanations rising along this channel is much localized. In the same manner the laccolithic bodies were heavily blanketed by thick impervious shale-formations that comprise the bulk of the Upper Cretaceous section. Fissures, dikes, and relatively pervious sedimentary beds were thus the principal channels of circulating mineralizers. Many nearly horizontal paths were followed by escaping solutions and also by clastic debris propelled with explosive violence. Thus the granodiorite magma is known to have crystallized under a moderate cover of 2 to 3.5 km and to have been so effectively blanketed that the escape of emanations was hindered. It is possible, therefore, that pressures existing in the magma chambers may have exceeded temporarily the normal pressure of a hydrostatic or even a rock-column to the surface.

The mechanism of emplacement of the magma in the different sills and laccolithic bodies can be partly inferred from the structures of the intrusive porphyries as well as by the relations of the different bodies to the main feeding channel. Linear parallelism of the hornblende or plagioclase phenocrysts in the sheets and laccolithic bodies is locally well defined, particularly near their upper or lower contacts. These structures indicate that the magma moved radially outward from near the feeding channel but the magma movements are locally somewhat complicated by the forms assumed by individual intrusive bodies. Portions of those bodies with which the present paper is chiefly concerned appear to have been fed by a single injection of magma which was of remarkably uniform composition. After this magma was emplaced further injections were confined to vertical dikes fed from deeper sources and to small bodies confined to the limits of the original feeder. These therefore failed to influence the course of crystallization and differentiation in the main laccolithic bodies.

Petrography and chemistry of the granodiorite porphyries

General features--Numerous thin sections were made of specimens collected from different parts of the intrusive bodies, and, although the different slides were generally similar, it was at first suspected that variations in composition of different parts of the bodies would be more than that actually found by subsequent chemical analysis, and also that certain parts of the bodies had been subjected to a regional enrichment in soda. The chemical analyses, however, definitely show that these petrographic differences are almost entirely the consequence of arrested crystallization in different stages of the magmatic history. In conjunction with the course of crystallization as shown in different specimens it was thus possible to establish the fact that the most pronounced changes in the composition of the magma occurred during the later stages of crystallization. Before considering these final stages, however, it is probably important to review briefly the evidence showing that the relatively sodic character of the granodiorite porphyry is not the result of a regional hydrothermal alteration but is clearly due to processes of differentiation that preceded the injections. If this is not a definitely established fact, then the conclusions regarding the final stages of crystallization may be open to question.

Representative specimens of the granodiorite porphyry were selected for chemical analyses from three positions in the intrusive body where the absence of nearby fissures insured against local alteration. The first of these came from the American Nettie sill, which is really the tapered edge of the thicker laccolithic body from which the two other specimens were taken. The specimen, numbered 1 in Table 1, came from near the base of the sill which is approximately 500 feet (150 m) thick at this position. Specimen number 2 came from near the base of the Dexter Creek laccolith about 8000 feet (2440 m) northeast of number 1, and specimen 3 came from near the top of the laccolith about 5000 feet (1520 m) northeast of number 1. Specimen 3 came from a position about 1000 feet (305 m) higher in the laccolith than that of number 2. The table of chemical and mineralogical composition shows that the three specimens represent a magma of uniform composition. (See Tables 1 and 1-A.)

Table 1--*Analyses of sodic granodiorite porphyries from Ouray County, Colorado*

Compound	1	2	3	Notes
SiO_2	65.38	65.02	65.35	1--Sodic granodiorite porphyry, sill above American Nettie mine, elevation 9700 feet, SW 1/4 Sec. 19, T. 44 N., R. 7 W., Ouray County, Colorado. Charles Milton, analyst.
Al_2O_3	15.41	15.83	16.09	
Fe_2O_3	1.97	2.13	2.69	
FeO	2.19	1.56	1.40	
MgO	1.43	1.14	1.33	2--Sodic granodiorite porphyry, Dexter Creek laccolith, elevation 9100 feet, NE 1/4 Sec. 20, T. 44 N., R. 7 W., Ouray County, Colorado. J. G. Fairchild, analyst.
CaO	2.87	3.32	2.52	
Na_2O	4.13	4.03	4.44	
K_2O	3.42	3.42	3.34	3--Sodic granodiorite porphyry, Dexter Creek laccolith, elevation 10,125 feet, NW 1/4 Sec. 20, T. 44 N., R. 7 W., Ouray County, Colorado. J. J. Fahey, analyst.
H_2O-	0.09	0.44	0.14	
H_2O+	1.29	1.24	1.26	
TiO_2	0.88	0.40	0.39	
CO_2	0.23	1.23	0.58	
P_2O_5	0.27	0.15	0.19	
MnO	0.09	0.12	0.06	
BaO	0.09	0.03	n.d.	
Cr_2O_3	n.d.	n.d.	0.03	
SO_3	n.d.	n.d.	0.04	
Totals	99.74	100.06	99.85	

Table 1-A—Calculated mineralogical composition and some features of the modal analyses of the granodiorite porphyries

Mineral	1		2	
Quartz		22.98		21.00
Orthoclase		15.11		17.29
Albite		34.58		33.50
Anorthite		12.04		13.53
Biotite[a]		9.17		6.90
Hornblende[a]		1.44		2.92
Magnetite		2.28		1.65
Hematite		0.20		0.90
Apatite		0.62		0.35
Totals		98.42		98.04
Approximate modal analyses				
Phenocrysts		26.00		51.10
Quartz	0.50		2.50	
Orthoclase	0.50		0.60	
Plagioclase	15.00 (An$_{55-25}$)		40.00 (An$_{25-30}$)[c]	
Ferromagnesians[a]	10.00		8.00	
Groundmass		74.00		48.90
Quartz	22.00		19.00	
Orthoclase	14.60		16.50	
Plagioclase	31.00 (An$_{20}$)		7.00 (An$_{25}$)	
Accessories[b]	6.40		6.40	
Totals		100.00		100.00

Notes: [a] Proportions of hornblende and biotite from modal analyses; these minerals largely resorbed to magnetite, chlorite, etc.

[b] Accessories include magnetite, hematite, chlorite, epidote, rutile, titanite, apatite, calcite, etc.

[c] Including some albite.

With the exception of the oxides of iron the differences between the other constituents are so small as to be of doubtful significance in the problems to be considered. The chemical and calculated mineral compositions show that the rocks may be defined either as sodic granodiorite or quartz monzonite, inasmuch as they differ from the average granodiorite and quartz monzonite as given by Daly and Johannsen in having a comparatively high ratio of soda to lime, and in possessing an intermediate potash-content, and from the average quartz monzonite in having higher total iron- and lower silica-contents. In conjunction with the evidence of reaction in the plagioclase and the development of sodic oligoclase and albite in the specimens from the thick laccolithic body, the high ratio of soda to lime suggested the possibility that the rocks had undergone albitization from some extraneous source.

A comparison of the petrographic features of specimen 1 from near the chilled margin of the American Nettie sill with those of the laccolith, however, shows that the formation of modal oligoclase and albite in the laccolith is entirely the result of more complete reaction and attainment of equilibrium between the earlier formed phenocrysts and the residual magmatic liquid. The crystallization in the sill was arrested at an earlier stage than in the thicker and larger laccolithic body with the consequence that the sill rock (specimen 1) contains only about 15 per cent by volume of plagioclase phenocrysts as compared to a rather uniform content of 40 per cent in the laccolith (specimens 2 and 3). Furthermore, the plagioclase phenocrysts of the sill rock are very strongly zoned from labradorite (An$_{55}$) to oligoclase (An$_{25}$) whereas zoning in the laccolithic rocks has been nearly all destroyed by reaction. In the sill rock there is, however, reaction between the andesine and labradorite cores of the crystals and the liquid to form orthoclase, affecting five to ten per cent of their volume. In the sill rock some but not all of the original hornblende and biotite remain unaltered, but in the laccolith the ferromagnesian minerals have completely reacted with the liquid to form sodic plagioclase, magnetite, hydromica, orthoclase, epidote, apatite, chlorite, rutile, calcite, quartz, and other minor reaction products. Without going into further detail on these differences in modal composition it seems evident that the development of albite and other sodic plagioclase in the laccolith was the result of long-continued reaction between the crystals and residual liquors of the magma and that an introduction of soda after crystallization could not have occurred. The sodic granodiorite magma must have formed by differentiation in underlying chambers before intrusion occurred, and the strong zoning of the intratelluric crystals suggests that fractionation coupled with some other process of differentiation may have been the principal cause of the high soda. Oscillatory zoning in the calcic plagioclase indicates the possibility either of some relative movement of the crystals and liquid or of changes in temperature of the liquid. In one rock at least ten major oscillations could be counted, with other minor ones.

The porphyries of the Ouray laccoliths are thus not altered by the introduction of foreign constituents. The statement in the Ouray folio (W. Cross, E. Howe, and J. D. Irving, Description of the Ouray Quadrangle, U. S. Geol. Surv. Geologic Atlas of the United States, Folio No. 153, p. 10, 1907) that a widespread uniform alteration had occurred as a result of mineralizing solutions may be interpreted, in the light of the above data, to mean that the porphyries crystallized under conditions such that the impervious blanket of shales nearly surrounding the laccoliths lessened the escape of the residual magmatic liquors and their effect on the crystals was much greater than would have occurred in a body intruded into a permeable environment. The later stages of crystallization consequently correspond more closely to and overlap the earlier stages of mineralization. This fact is brought out clearly by a comparison of processes of igneous metamorphism and mineralization that took place near the conduit from which the magma was erupted, with the later stages of crystallization in the laccolithic bodies. That such a correspondence exists is well known and has been often mentioned in geologic literature (N. L. Bowen, The broader story of magmatic differentiation, briefly told: Ore deposits of the Western States (Lindgren volume), pp. 107-108, Amer. Inst. Min. Met. Eng., New York, 1933). It is not the purpose of this paper to detail the parallelism of these two processes, but to emphasize a few special features that are believed to be of more than ordinary significance.

State of oxidation of the iron in relation to stages of crystallization

The chemical analyses of the porphyries show marked differences in the state of oxidation of the iron though differences in the total amounts of iron fall within the limits of variation shown by the other constituents, a variation of less than one-half of one per cent. On the basis of total iron as Fe_2O_3, the relative percentage of ferric iron in the porphyry from the sill is 44.5 per cent whereas in the porphyries from the laccolith the percentages of ferric iron are 55 and 63.3. The high ferric-oxide content of the laccolithic bodies is significant and the microscopic study of polished surfaces of the three rocks show that this does not represent differences in the original magma, but represents an oxidation of part of the ferrous iron during later stages of crystallization. This fact is established by the mode of occurrence of hematite in the oxidized magmas. The principal iron-ore that crystallized from the sill-porphyry is magnetite, whereas hematite is very scarce and represented chiefly by thin scales in the altered biotite from which it was derived by breakdown of this molecule during early stages of reaction. Magnetite occurs in several generations in this rock, first as large grains of comparatively early crystallization, second as decomposition-products of the ferromagnesian silicates, and finally as extremely minute grains that crystallized late in the groundmass. All of these different forms of magnetite are unoxidized in the sill rock. In the laccolithic porphyries the same different generations of magnetite were formed, even to the minute groundmass octahedrons, so that even as late as the beginning of crystallization of quartz and orthoclase in the groundmass,magnetite was in equilibrium with the residual magmatic liquids.

However, in the porphyry from the base of the laccolith, in which 55 per cent of the total iron is in the ferric state, all generations of the magnetite are partly changed to hematite though retaining their characteristic form and occurrence. In the groundmass the minute octahedra are in part unaltered magnetite and in part completely or partly altered to hematite. The larger octahedrons of earlier crystallization are approximately one-third changed to hematite, which occurs in the form of lamellae, and almost exactly the same proportion of hematite is found in each individual crystal. There is a slight suggestion, however, that oxidation proceeded somewhat more rapidly in the outer portions of the crystal. In the porphyry from near the top of the laccolith, in which 63 per cent of the iron is in the ferric state, the magnetite grains of all generations are almost completely changed to hematite. The relative proportions of magnetite and hematite as determined by Rosiwal measurements of polished sections of the rocks are shown in Table 2. The change of magnetite to hematite probably does not represent the total amount of change from ferrous to ferric iron, as the additional amounts of epidote, chlorite, and possibly other secondary silicates in the laccolithic rocks probably account for part of the increment of ferric iron. It is perhaps important to note that calcite, one of the latest if not the latest mineral to crystallize in the porphyries, is not accompanied by hematite. In minute pores of the rocks in the groundmass there are also small grains and blebs of sulphides, which seem to be chiefly pyrite, with probably a little chalcopyrite. The measured proportion of pyrite, subject, however, to considerable error because of the small size of the grains, ranges from 0.03 to 0.06 per cent.

Table 2--Approximate proportions of magnetite, hematite, and sulphides in granodiorite porphyries

Mineral	1	2	3
Magnetite	2.28	1.65	0.21
Hematite	0.20	0.90	1.84
Sulphide	.02	.06	.04

Inasmuch as an amount of sulphide probably less than half of that in the laccolith rocks also occurs in the unoxidized sill-porphyry, sulphides had started to separate from the magma before the oxidation of magnetite began. As will be mentioned again later this accords with evidence from high-temperature veins in the zone of igneous metamorphism, showing that some pyrite was deposited in these veins before the formation of hematite.

From these mineralogical and chemical changes that have occurred in the crystallizing porphyries, and because we have shown that the porphyry laccoliths and sills were protected from extraneous influences, the conclusion must be made that some process entirely inherent in the properties of the magma itself was responsible for the oxidation of iron during later stages of crystallization. I cannot emphasize too strongly that I believe the evidence regarding the protection of the sills and laccoliths from outside influence is conclusive. Furthermore even if such changes could be produced by introduction of hydrothermal liquids or vapors the results of change are so uniformly distributed throughout the laccolithic bodies, and so definitely related to stages of crystallization, that the mechanism of the introduction would be exceedingly difficult to conceive.

Possible causes of the change in equilibrium between the oxides of iron

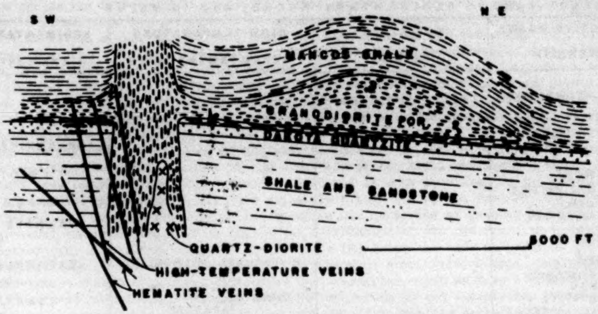
An attempt will be made to show that the change in equilibrium between the oxides of iron was caused by a relatively sudden relief of pressure on the magma-chambers. This resulted in a period of comparatively short duration within which internal adjustments between the residual liquors of the magma, the crystallized material, and the suddenly evolved vapors caused partial oxidation of the iron. This theory contains nothing new of physical-chemical nature inasmuch as strikingly similar phenomena have often been described in connection with lava-flows, but so far as I know there are few if any detailed descriptions of such phenomena in connection with deep-seated magma-bodies removed from the possible influence of contribution by atmospheric or resurgent gases. The particular geologic relations of the zone of igneous metamorphism and mineralization at Ouray to the crystallizing magma also permit the correlating of certain critical events within the magma with those taking place under exomorphic conditions.

Of the possible external causes of the phenomena the absorption of water or vapors from the surrounding shales during the later stages of crystallization meets with practically the same mechanical difficulties as mentioned for post-consolidation hydrothermal or gaseous agencies. Furthermore Daubree's capillary hypothesis seems to be the only one applicable to the conditions inasmuch as no large bodies of shale are engulfed in the magma. The amounts of capillary or resurgent vapor required by this hypothesis also seem entirely out of proportion to what might be obtained from the comparatively impervious shales. Without mentioning further possibilities of this kind it is probable that the primary cause can be immediately limited to either a change of pressure or temperature or of both. A simple change in temperature, even assuming a moderately delicate equilibrium between various compounds involved, can be almost as readily eliminated as the possible external causes. Inasmuch as the more rapidly chilled porphyry of the sills and margins of the laccoliths has undergone cooling through the same temperature-range as other parts of the magma, oxidation of the iron should have occurred within the appropriate temperature-range. Absence from the more rapidly chilled margins of vapors that might be critical to the reaction can hardly account for the difference, since some calcite and other hydrous-reaction products also are found in these chilled rocks. Some oxidation of the iron occured even in these chilled margins during earlier stages of crystallization, but in comparison with other parts of the laccolithic bodies the amount of this oxidation does not appreciably affect the problem as a whole.

The possibility that a change in pressure on the magma was sufficient to cause oxidation of the iron is supported by a considerable body of evidence. This is shown in the geologic relations within the zone of igneous metamorphism near the main channel-way through which the magma was intruded. In order to present this evidence a comparison of critical events that occurred in the zone of metamorphism with the later stages of crystallization of the magma is necessary.

Comparison of exomorphic processes and crystallization of the magma

It may be well to emphasize first that the processes of rock-alteration and mineralization to be described are confined to a zone close to the channel through which the magma was originally erupted, whereas the later stages of crystallization with which they are compared represent widespread effects throughout the isolated laccolithic body (Fig. 1). It is believed that this method



SPECIMEN NUMBERS SHOW RELATIVE POSITIONS OF ANALYZED SPECIMENS; SPEC. I LIES 2500 FT NORTH OF SECTION; VEINS STRIKE ABOUT E - W

FIGURE I—GENERALIZED GEOLOGIC CROSS-SECTION SHOWING RELATION OF DEXTER CREEK LACCOLITH TO FEEDING CHANNEL OF THE OURAY GRANODIORITE MAGMA

is justified inasmuch as we are thus able to compare changes occurring in a protected magma-body with the essentially simultaneous and magnified effects produced in a permeable channel-way overlying a magma of similar composition. The protected body is thus free from the endomorphic alterations that commonly obscure details in the margins of contact-zones. As the channel-way is narrow, even though perhaps very deep, crystallization in the upper part must have taken place nearly as rapidly as, if not more rapidly than, in the thicker laccoliths. This condition is indicated by the fact that only one small intrusive body a few hundred feet across invaded the neck after the porphyry-intrusions. This body is a quartz-diorite relatively high in potash and thus close to the composition of the granodiorite. There are other features of the late crystallization in the porphyries of the channel-way which indicate that a portion of the granodiorite in the upper part of the neck had actually completed crystallization before the porphyry of the laccolith. The evidence for correlation of these crystallization-stages will appear below.

The comparison between the crystallization-stages of the magmas and the exomorphic processes is best made by diagrammatic illustration, though certain details of the order of formation and in the position of reaction-products in the series are difficult to show in this manner (see Table 3). Certain products have formed more or less in definite or pseudo reaction-series that have a considerable range of stability whereas other products have limited and easily recognized positions in the series. In addition to the different minerals belonging to one or the other of the above series there are at least several minerals occupying a definite position in the diagram that for want of a shorter term may be called a physico-chemical unconformity. It seems reasonable to suppose, and there is evidence to show, that a larger number of unconformities of this kind exist but the one illustrated in the diagram is of such prominence that no difficulty is encountered in recognizing it in petrologic studies of the mineral sequences. This refers of course to the formation of hematite, immediately followed by epidote, chlorite, and possibly other minerals with an unusually high content of ferric iron. Inasmuch as chlorite and epidote also form at other positions in the series and as comparative analyses and petrographic data that might show differences in composition would require much detailed work, only those sequences are shown in which hematite is present.

The simplest sequence of the different groups is that shown by the hematite-veins. These veins occur in greatest abundance west of and within four thousand feet of the channel-way. As most of the fissuring parallels that of the earlier east-west dikes these veins have their greatest

TABLE 3 — PARAGENETIC RELATIONS OF MINERALS IN GRANODIORITE PORPHYRY, CONTACT-ZONE IN SEDIMENTARY ROCKS, AND IN VEINS

GRANODIORITE MAGMA OF LACCOLITH	HEMATITE VEINS	HIGH-TEMPERATURE REPLACEMENT VEINS	SEDIMENTARY ROCKS IN EXOMORPHIC ZONE
LABRADORITE | HORNBLENDE MAGNETITE ANDESINE ↓ BIOTITE OLIGOCLASE MAG. ORTH. QTZ. RUTILE HEM. ALBITE CHLORITE ALLANITE (1) ORTHOCLASE QUARTZ- HYDROMICA MAG. APATITE ALLANITE (2) CHLORITE ETC. PYRITE ↓	PYRITIZED AND SERICITIZED COUNTRY ROCKS FISSURING AND BRECCIATION	ORTHOCLASE-MICROCLINE QUARTZ- MAGNETITE APATITE ALLANITE (2) PYRITE SHEARING,-	LABRADORITE-HORNBLEN (BIOTITE) MAGNETITE ALBITE CHLORITE ORTHOCLASE-- -- HYDROMICA QUARTZ-- -- APATITE RUTILE-- ETC.
HEMATITE EPIDOTE-CHLORITE QUARTZ,- SULPHIDE[C] CALCITE	HEMATITE EPIDOTE-THURINGITE[A] QUARTZ;[A] CALCITE[A]	MAGNETITE-HEM.[B] THURINGITE QUARTZ CHALCOPYRITE-SPHAL. CALCITE	HEMATITE EPIDOTE-CHLORITE QUARTZ CALCITE

A- MAY OR MAY NOT BE PRESENT B- IN SMALL AMOUNTS C- SOME SULPHIDE DOUBTLESS BELONGS HERE BUT PARAGENETIC RELATIONS ARE OBSCURE

extent in this direction. Close to the channel-way, however, numerous small hematite-veins cut the rocks in every direction. One fact that is quite evident from the general distribution of the veins and their relations to other mineralized fissures is that the hematite-veins bear no definite structural relation to other kinds of mineral deposits; in places they are entirely independent and in others follow earlier zones or cut across them. This structural relation thus shows that the vapors or emanations depositing hematite invaded the exomorphic zone immediately following a period of widespread new fracturing and reopening of old fissures. This fracturing thus appears sufficient to result in a pronounced relief of pressure on the adjacent magma-bodies. The simple hematite-veins, however, afford no direct evidence in themselves as to the correlation of this physico-chemical unconformity with the formation of hematite in the laccoliths or in the igneous bodies of the channel-way.

The high-temperature replacement-veins close to the channel-way, however, have a more complex mineralogy and show some significant parallelisms with the stages of crystallization in the magma. These veins occur in rather tight shear-zones and along irregular narrow fractures in both sedimentary rocks and porphyry-dikes. The sedimentary beds are chiefly sandstone or sandy shales of the Carboniferous formations and are thus on the average more siliceous in composition than the magma itself. The effects of the wall-rocks on these high-temperature series near the channel-way thus should preserve their normal course rather than introduce confusing reactions. Mineralogically these veins are characterized by the abundant development of pinkish orthoclase and microcline with comparatively narrow veins of massive or plumose magnetite. Numerous minor accessory minerals accompany these products, but those of special interest include apatite, and allanite of a deep-brown pleochroic variety referred to in the tables as allanite (2). What appears to be exactly this same allanite also occurs as a reaction product rimming large crystals of greenish-brown allanite in the groundmass of the granodiorite porphyries. This mineral occurs in the sill-porphyries that had solidified before the oxidation of the magnetite to hematite. Late apatite of this stage is also abundant in all of the porphyries, but is not of course nearly as concentrated as in the high-temperature veins. Following the formation of magnetite considerable pyrite was introduced in the veins. This mineral and the chalcopyrite, to be mentioned again later, form the principal ore, which has been mined locally for its gold-content. During the formation of pyrite, however, there was some shearing and fissuring along the vein-zones which distorted, crushed, and fractured the previously formed minerals. Immediately following this episode came the introduction of small additional amounts of magnetite accompanied by hematite. These iron oxides accompany or are followed by thuringite and quartz. The quartz is characterized by the abundance of vacuoles and cavities partly filled with liquid and gas. Following the quartz and chlorite, chalcopyrite and a little sphalerite were deposited. If pyrite accompanied the chalcopyrite the relative amount was small. The high-temperature veins thus clearly show the presence of the physico-chemical unconformity at which ferric iron minerals were deposited, but, because of the tightness of the veins and their dominant replacement-origin, the amount of hematite actually introduced is much less than in the open hematite-veins. Furthermore these high-temperature veins lie within 400 to 500 feet of exposed porphyries of the channel-way, whereas the bulk of the hematite was deposited at greater distances, averaging perhaps several thousand feet. If we accept the correlation of the pre-hematite minerals of the veins--orthoclase, microcline, apatite, and allanite (2)--with the same minerals of the porphyries, and the correlation of the co- and post-hematite minerals--thuringite, quartz, and later sulphides --with the latest stages of crystallization of the porphyries, then we have a reasonably definite correlation of the hematite-unconformity with that occurring in the laccolithic bodies. Sedimentary rocks in the exomorphic zone within less than 100 feet from the quartz-diorite of the channel-way exhibit the same general metamorphic sequence, as shown by the table; however, the possibility that the metamorphosed rocks were originally somewhat more calcic than the magma does not permit the exact timing of the formation of labradorite and hornblende, inasmuch as reactions may have delayed its time-sequence in reference to these same minerals in the magma. The epidote-quartz-hematite unconformity, however, is doubtless the same. A similar succession could be given for limestone contact-zones a few thousand feet from the channel, but these are further complicated by pseudo reaction-series. Simple pyrite-veins several thousand feet distant from the channel-way are also interrupted by renewed fissuring and deposition of hematite.

With regard to the porphyries of the channel-way some of these examined showed that magnetite had not been oxidized even in the groundmass though it is partly replaced by quartz, pyrite, chalcopyrite, and other pre- or post-hematite minerals. The quartz-diorite body however retained sufficient residual magmatic liquors to cause partial (about 1/3) oxidation of the magnetite within a few feet of its contact with sedimentary rocks. A marked difference is noted, however, in the form which the hematite takes in the magnetite crystals of the quartz-diorite. The hematite-lamellae common to the crystals of the porphyries are absent but instead the hematite occurs in an irregular intergrowth of the "mutual boundary-type". Whether or not this difference is significant is not apparent. Possibly the temperature of the residual liquors and the state of crystallization in the groundmass may be factors.

The state of crystallization of the magmas and the composition of the residual magmatic liquors and gases are important features to be considered in relation to the causes of this change in equilibrium. The question may well be raised whether this phenomenon properly belongs to what is called magmatic stages of crystallization. That there was still much residual vapor and liquor in the rocks at the time of the oxidation of the iron is shown by the fact that the deposition of thuringite, epidote, calcite, and other co-hematite and post-hematite minerals was one of the most extensive kinds of mineralization in the area. Quartz is one of the more abundant minerals of this late sequence and it thus seems probable that the groundmass quartz of the porphyries had not completed its crystallization. In the quartz-diorite, however, which is a granitic-textured rock there are no small groundmass magnetite-octahedrons though there are perhaps traces of hematite-plates that are not pseudomorphic after magnetite. It may be inferred that probably more than 90 per cent of the porphyry-magma had crystallized, but how much more is not evident. In the quartz-diorite there is little indication, though a study of vacuoles and inclusions in the quartz may give some light on this problem. The quartz in this rock, however, shows a marked tendency to the formation of fingers and veinlets that penetrate previously formed minerals along partings or cracks. These may possibly represent the consequence of the latest stages of crystallization accompanying and following the hematite-unconformity.

Geochemical and geophysical inferences

It is unnecessary at this place to consider definite physical-chemical reactions that cause oxidation of ferrous iron, but certain general inferences derived from a comparison of the magmatic crystallization and the contemporaneous mineralization will be considered first. Two postulates based upon the field-observations already detailed are fundamental to this comparative study: First, that a release of pressure caused the oxidation of ferrous iron, and second, that the release of pressure permitted the formation of a differentiated distillate from the magma-hood which is represented by the ferric iron-bearing emanations. Although there is no apparent evidence of the composition of this distillate, the presumption that it contained a volatile halide of ferric iron seems to be supported by a considerable body of evidence contained in geologic literature.

During the earlier stages of mineralization we may picture the magma as composed of a number of solid phases, already crystallized from the liquid, plus a certain amount of intercrystal material composed of mutually soluble components in a single phase or perhaps in several phases. Using the term phase in the broader sense we may consider the several systems as follows: (1) A system composed of crystalline minerals plus one phase (fluid), (2) a system composed of crystalline minerals plus two phases (liquid plus gas), and (3) a system composed of crystalline minerals plus several immiscible liquids with or without a gas-phase. Inasmuch as no system of immiscible liquids has been definitely established for natural melts we may ignore such a system in the subsequent discussion without intent to imply, however, that such systems may not exist under certain conditions. Both of the other systems include one common phase, that of the crystalline minerals, which does not enter directly into the mechanism of transportation from the magma-hood to the surrounding rocks. Therefore, in referring to the mode by which mineral constituents are transferred from the magma-hood to the immediately surrounding exomorphic zone the terms "single-phase transfer" and "two-phase transfer" will be employed in connection with their respective systems. In single-phase transfer critical phenomena may or may not be involved (P. Niggli, Ore-deposits of magmatic origin--translated by H. C. Boydell, London, 1929). In two-phase transfer the distillate is presumed to leave the magma-hood moderately or highly differentiated and the vapor-phase may be originally acid. There are also some geophysicists who further contend that certain of these evolved phases may pass continuously from one to the other without appreciable discontinuity (G. W. Morey, J. Geol., v. 32, pp. 291-295, 1924), or the intervention of critical phenomena.

The particular events that took place in the Ouray granodiorite and its exomorphic zone may be briefly considered in connection with these different modes of transfer. Fracturing of the roof above the central vent apparently released the pressure on the magma-system suddenly and disturbed the equilibrium, forming a highly differentiated distillate, which deposited hematite in the exomorphic zone. Because of the composition of the precipitate and according to our premises the transferring phase must have been a gas. Whatever the state of the magmetic residues their freezing point must have been suddenly raised, causing a rapid precipitation of solids. The temperature of the evolved-gas phase was probably much lowered relative to that of the residual magmatic liquids. In consequence of these changes and the lag in attainment of a new equilibrium, an episode of chemical and physical reactions resulted that doubtless were responsible for the oxidation of ferrous iron in the magma-hood. The fact that these processes were episodic is shown by the relation of hematite-deposition to the normal sequence of ore-deposition in the exomorphic zone. The change from ferrous iron to magnetite or hematite is normally an exothermic reaction and the expansion was therefore not purely adiabatic.

Hence we may conclude that the deposition of hematite belongs to system (2) of those enumerated above, in which there exists a crystalline phase in contact with interstitial liquid- and gas-phases. The liquid-phase as a consequence of released pressure in the magma-hood is undergoing boiling. The magma-system, however, reacts to establish an equilibrium in which the loss of heat by expansion of the dissolved gas is offset by increased rapidity of crystallization. This new equilibrium which the system approaches is that described by N. L. Bowen (Op. cit., Ore-deposits of the Western States, pp. 122-123) as the "second boiling-point," wherein the rate of evolution of a gas-phase is in approximate equilibrium with subtraction of crystals from the liquid. If no internal source of heat-energy is provided by the system, the temperature must first fall rapidly until approximate equilibrium is reached at a fairly constant back-pressure. However, any heat produced by the oxidation of ferrous iron shifts this equilibrium in such a direction as to increase the evolution of gas. Then if fractional distillation of the gas is the direct cause of the oxidation-process, as we have implied, the reaction must proceed with increasing violence until either the reacting products are exhausted or until the external pressure becomes sufficiently great to cause disappearance of the gas-phase. The sequence of mineralization in the high-temperature veins indicates that the evolution of ferric iron-bearing emanations was episodic and hence we may conclude that the gas-phase was forced by pressure to disappear. If such is actually the fact, then the pre- and post-hematite stages of mineralization must belong to system (1), wherein only a single phase is involved in molecular transportation from the magma-hood to the surrounding rocks. This hypothesis may be applied to the processes of mineralization to determine if they can be satisfactorily explained.

Beginning with the earlier stages of mineralization in the veins the most abundant of the transferred mineral molecules were those of orthoclase, microcline, quartz, magnetite, apatite, and pyrite, though minor molecules such as those of allanite (?), zircon, and rutile seem to be particularly significant. It is noteworthy that these are deposited in the exomorphic zone in essentially the same sequence as in the magma, and in the case of allanite (2) in nearly the same crystallographic form. A particular exception to the crystallographic identity of the mineral forms is that shown by the potash-feldspar molecule, which was deposited in the exomorphic zone as microcline as well as orthoclase. Furtheremore, it is seen that by the time of the disturbances initiating the influx of hematite, the molecules of potash-feldspar, quartz, magnetite, pyrite, and other minerals were in solid crystal-form subject to distortion and fracturing by forces acting within the rocks. There scarcely can be any doubt that the minerals were deposited either directly from the transferring agent in their present form, or else that the transformation of the elements to the complex silicate, oxide, and sulphide molecules was a very rapid process. Applying the principles of phase-equilibria to the magma-system and high-temperature veins, it seems evident that the transferring agent in equilibrium with orthoclase in the magmatic residues must be identical with the agent in equilibrium with orthoclase in the veins. The change in crystallographic form of part of the feldspar-molecule may be attributed to a loss of energy from the agent, or would perhaps indicate more specifically that a critical pressure-gradient existed temporarily and that microcline was deposited because its molal volume is greater than that of orthoclase. This then would seem to support the previous indications that the transferring agent during the greater part of the pre- and post-hematite stages was a single phase.

Even assuming that certain fundamental characters of the transferring agents are established by these relations, other features of the mechanism and paragenetic relations of the minerals remain that are not accounted for by the processes so far considered. The most important of these are the mechanism by which the iron is oxidized, the cause of the disappearance of the gas-phase, and the occurrence of ferric iron-, magnesium-, and calcium-bearing silicates in the vein-sequence following the hematite-unconformity. In order to relate these different phenomena the structure of the magma-hood and the geophysical conditions must be considered in more detail. According to E. S. Larsen's (The temperatures of magmas, Amer. Mineralogist, v. 14, pp. 81-94, 1929) estimates the crystallization of a magma of intermediate composition such as granodiorite may be assumed to take place within the temperature range of 573° to 870° C. The release of pressure on the single-phase magma-fraction at the time of the hematite-unconformity must first be sufficient to have caused separation of an additional phase within the pores of the crystallizing granodiorite.

The strength of the predominantly crystallized rock must therefore have been nearly or quite sufficient to support the surrounding earth-pressure, as well as the internal pressure developed within the system. That these conditions were met at least locally can hardly be doubted though slight distortion in the crystal-meshes at this stage is shown perhaps by tongues and veinlets of late quartz that penetrate the crystals of the quartz-diorite. At other places in the District, however, there seems to be evidence that parts of the magma-hood failed to withstand the internal pressure and were destroyed with explosive violence. These explosions are believed to be manifested in the injection of clastic debris, partially molten rock, and fragments of the disrupted igneous rocks. While the relations of these explosive eruptions to stages of mineralization cannot be described in this paper, they present convincing evidence that the pressures ordinarily assumed to hold during processes of mineralization have been greatly underestimated, and that their upper limit is probably even greater than the weight of the overlying rock-column because of restrictions in the effective area on which the pressure is applied. In the absence of this explosive phenomena in the area under consideration the strength of the magma-hood must have been adequate so that when fissures were formed in the wall rocks a large amount of new open space was provided. The single-phase magma-fraction in the pores of the granodiorite would thus be temporarily subjected to an extremely low external pressure. This would be well below even the critical pressure of any phase at the existing temperature, and a new phase would come into existence within the pores of the granodiorite. We may now turn to see what happened in the exomorphic zone.

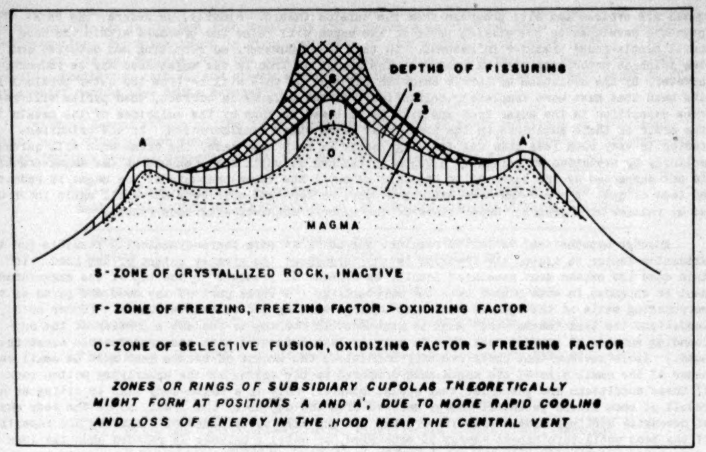
It is noteworthy that iron, which was actually depositing as sulphide just before the pressure was released, was the metal present in the residues in greatest concentration, and that within the assumed limits of temperature its vapor-pressure as chloride is high. Inasmuch as a new equilibrium must be established when two new phases are formed, the most volatile element or compound would be first evolved in a gas-phase. Hydrogen, halides, and some sulphur and oxides of carbon would doubtless be the most abundant of the volatile gases. Within the temperature-limits some of the most volatile chlorides are those of iron, copper, aluminum, arsenic, antimony, and bismuth. Inasmuch as quartz was the chief non-metallic constituent depositing with the sulphide-phase preceding the hematite-unconformity, alumina would not be present in the residues in sufficient quantity to be an important constituent of the evolved gases. Arsenic, antimony, and bismuth were present presumably only in very small concentration. Thus ferric chloride would be a compound of the evolved vapors, and the only one that would form an abundant solid phase at a temperature which would permit precipitation. Water, carbon dioxide, and hydrogen sulphide left no recognizable evidence of their presence in the evolved vapors, but from our premise, the temperature of the evolved gas immediately adjacent to the walls of openings would certainly be too high for the formation of hydrous acid phases. Not until these gases reached rock of temperature so low that undissociated water-vapor could exist in quantity would they be capable of producing recognizable alteration. These gases then may be supposed to have escaped into the pores and fissures of the rocks.

Is there any physical-chemical mechanism inherent in this process by which ferrous iron might be oxidized to ferric iron? At the temperatures existing we may consider the hyperfusible constituents, as suggested by N. L. Bowen (The broader story of magmatic differentiation briefly told, Ore-deposits of the Western States, Lindgren Volume, Amer. Inst. Min. Met. Eng., pp. 118-120, New York, 1933), to be present partly as ions or dissociated gas-molecules. Those listed are H, O, H+, OH-, CO_2, S-, Cl-, F-, H_2O, H_2S, CO_3^-, S, and many others. With the sudden release of pressure upon the system the most diffusive and volatile gas in the magma-fraction will be evolved in greatest amount. It seems probable that the gas first evolved will contain therefore a proportion of hydrogen from the dissociated water-molecules. Other light and abundant gases will follow in their turn but the magma-fraction is of necessity enriched in the heavier and less abundant hydroxyl ions or oxygen molecules. As ferrous iron is one of the more abundant of the oxidizable molecules some of it must be oxidized to ferric iron. Chlorine gas may be considered as a possible catalytic agent for this oxidation-process. One might expect that sulphur would be oxidized to some extent, but because a greater potential may be required to oxidize sulphur so that it combines with available oxygen to form a stable compound, iron would perhaps take first preference. It will be shown later that for some reason sulphur is not oxidized to its highest state until the magma-fraction is greatly impoverished in iron or until the iron is largely in the higher state of oxidation.

Thus the mechanism of the expansion-process seems to be amply demonstrated by the structural conditions and by the solid distillation-product in the fissures. However, as shown by the succeeding mineral deposition in the high-temperature veins, the magma-system must have returned immediately to the condition originally assumed, that is, solid granodiorite plus a single-phase residue. This is shown by the fact that the immediately ensuing mineral-sequence consists of thuringite, epidote, quartz, and chalcopyrite deposited in the order named. Thus in some way the temporary release of pressure on the system has increased the relative concentration of copper, silica, magnesia, lime, ferric iron, and alumina in the single-phase magma-residues. How this has happened may be deduced by considering several factors: (1) The structure and shape of the receding magma-hood, (2) the oxidation-factor inherent in the magma-residues, and (3) the freezing factor, inherent in the loss of gas from the magma-system during expansion (see Fig. 2).

At the time of fissuring we may imagine that a given thickness of the outer zone of the magma-body had crystallized forming a hood whose rigidity permitted fissuring and fracturing. The thickness of this relatively rigid but weak hood would be greatest near the top of the body and would decrease along the sides of the body in depth (W. H. Emmons, On the mechanism of the deposition of certain metalliferous lode-systems associated with granitic batholiths: Ore-deposits of the Western States, Lindgren Volume, Amer. Inst. Min. Met. Eng., New York, 1933). Thus the fissures that formed at the time of the hematite-unconformity could extend downward into the hood a sufficient distance to tap that active magma-fraction in which the greatest concentration of volatiles had occurred. Immediately the pressure is released upon this single-phase active fraction two opposing factors are operative, which we have called the freezing factor and the oxidation-factor. The evolution of gas from the fraction would cause freezing in some direct proportion to the amount of gas evolved, and in inverse proportion to the amount of heat generated by the consequent oxidation of iron. Thus at some distance below the topmost parts of the hood, within which no oxidation occurred, as we have shown, there would exist a zone of maximum generation of heat determined by the relative concentration of oxidizing agents and of iron in the magma-fraction. Below this zone the amount of oxidation will decrease, both because the lower parts of the magma-hood are incapable of withstanding the release of pressure and because the relative concentration of gases in the magma-fraction would be much less. We may now consider the possible variants to which the system is subject in the particular position where maximum oxidation occurs. Let us assume first that in this position the oxidation-factor just exceeds the freezing factor by a small amount. Selective fusion will take place and freezing cannot be resumed until additional gas is evolved. The system will return to a solid plus a liquid-phase, with or without gas, in which the liquid-phase is in excess of that originally present.

Before considering what happens to this new liquid-phase it is necessary to take into ac-


DEPTHS OF FISSURING
1
2
3
S
F
O
A
A'
MAGMA
S-ZONE OF CRYSTALLIZED ROCK, INACTIVE
F-ZONE OF FREEZING, FREEZING FACTOR > OXIDIZING FACTOR
O-ZONE OF SELECTIVE FUSION, OXIDIZING FACTOR > FREEZING FACTOR

ZONES OR RINGS OF SUBSIDIARY CUPOLAS THEORETICALLY MIGHT FORM AT POSITIONS A AND A', DUE TO MORE RAPID COOLING AND LOSS OF ENERGY IN THE HOOD NEAR THE CENTRAL VENT

FIGURE 2—DIAGRAMMATIC SECTION OF A MAGMA-HOOD, SHOWING ZONES OF CRYSTALLIZATION AND DISTRIBUTION OF POTENTIAL ENERGY

count what has happened in the meantime in the outer parts of the magma-hood. We have already mentioned that no oxidation could take place at the outermost edge of the hood because it was almost completely solidified, and thus had not enough liquid magma-fraction in the pores. Therefore at an intermediate position in the hood some oxidation could occur but its factor must obviously be less than the freezing factor since in the center of the hood we had assumed that oxidation exceeded freezing by only a small amount. Thus the outer parts of the hood would gradually or quickly freeze, the rate depending upon the rate of evolution of gas. This freezing would close the pores of the granodiorite until the back-pressure upon the deeper fractions reached the point at which three phases could no longer exist. Evolution of a single-phase fluid through the pores of the hood would then be resumed. This state would represent the ensuing deposition of minerals in the high-temperature veins following the hematite-unconformity. Inasmuch as a small amount of additional solid has been dissolved in the liquid-phase in the center of the hood, new compounds will appear in the products of mineralization. Silica would be the most abundant of the new components and the chlorite formed by earlier reaction, being a hydrous mineral, would probably be included in this redissolved fraction. Ferric iron would be more abundant than in the previous liquid and consequently will appear in the new products of single-phase deposition, thus accounting for the thuringite and epidote. After the deposition of thuringite, epidote, and quartz, chalcopyrite rather than the original pyrite is the chief sulphide mineral, indicating that most of the iron was in the ferric state and has been exhausted by combination with silica. Copper and ferrous iron remaining combine to form chalcopyrite which is evolved until exhausted, when zinc and lead sulphides will follow if no further interruption takes place. This is in accordance with the normal order of abundance and with the paragenetic relations of these elements in the mineral deposits. [According to the normal order of abundance of elements in the rocks of the crust the primary order of deposition, according to the mechanism presented, should be iron, copper, zinc, and lead. This is actually the order in the area under discussion. However, in many mesothermal deposits sphalerite precedes chalcopyrite. The reasons for this reversal are probably related to the mechanism of concentration in the magma-hood and to the partial pressures of the different sulphide molecules containing copper. These factors will be discussed in a more detailed paper in preparation.]

Two other variations of this system are possible and, though they do not apply to the particular conditions in the Ouray granodiorite, they are of importance in relation to problems of volcanology and of mineral deposits as a whole. We may suppose that in the central part of the magma-hood where maximum oxidation occurred the oxidation-factor just equals or is a little less than the freezing factor. Freezing will then occur throughout the hood in proportion as the gases are evolved and will progress from the outside inward. Finally, as before, the back-pressure developed by the closing pores of the magma will raise the pressure within the hood until single-phase transfer is resumed. In this case, however, no remelting has occurred and the sulphide deposition will be resumed. The amount of iron in the magma-hood may be reduced, however, by the evolution of ferric chloride but most of this will be from the outer portions of the hood that have more completely solidified. If the balance is correct, then pyrite will resume deposition in the outer zone and will be followed in turn by the sulphides of the metals in the order of their abundance in the particular magma under consideration. If the oxidation-factor is very much less than the freezing factor in this same case, the magma-hood will quickly solidify by evolution of gas until a depth is reached at which the pressure on the magma-fraction is not supported by the surrounding crystals or until the vapor-pressure of the magma is reduced by loss of gas. A new magma-hood will then start to form and will continue until again interrupted by release of pressure. Repetitions of the mineral sequence will thus result.

Another hypothetical variation remains, supposing it were thermodynamically possible for the oxidation-factor to exceed the freezing factor throughout the greater extent of the hood. In this case the excess heat developed locally by release of pressure in the top of the magma-hood must be expended in some manner upon the surroundings. A large part of the hood and parts of the surrounding walls of the igneous mass must undergo melting and selective fusion. [Under such conditions the term "magma-hood" must be broadened in meaning to include a portion of the surrounding aureole of invaded rock that is more or less saturated with the hyperfusible constituents.] It is obvious that under ordinary conditions the amount of excess heat must be small because of the small size of the magma-hood compared to the volume of the underlying molten rock. If these conditions are possible, they apply, however, only to a magma-body that is rising as a result of some excess potential-energy derived from the depths of the crust, since the body must of necessity continue upward--but interrupted now and then by episodes of fissuring and remelting of the hood until this excess energy is exhausted, or until a balance is reached when the loss of heat by radiation through the crust and by the escape of emanations reduces the oxidation-factor so that it no longer exceeds the freezing factor. A magma so situated with respect to the surface of the Earth that this balance is reached, must then enter its period of decadence and a permanent magma-hood would form. The retreat of this hood to depth initiates the processes of mineralization.

It is probable that a magma-body rising in this matter from some large flat-topped body in depth will develop a more rapidly tapering cross-section when the loss of energy becomes more rapid by reason of the existence of open fissures in the surrounding rocks. Theoretically its shape would be controlled in a homogeneous medium by the kind and amount of stresses existing in the crust, the reaction of the crust to fissuring, and by the rapidity with which heat was lost whether by fissuring or by radiation. When the top of the body becomes very narrow, or perhaps cone-shaped, if in a region of undirected stresses, the greatest concentration of light oxidizing agents of the body will reside near this apex as a result of their gradual collection here during the previous stages of advance. If the energy remaining in this apex is sufficiently great, the magma may melt its way upward until the surface of the Earth is reached and volcanism as we see it will be initiated. If the excess energy is fairly great, comparatively quiet eruptions would result, and the magma would flow as lava from the volcano. When most of this is expended, a magma-hood would form in the throat of the volcano and would grow downward indefinitely unless crustal disturbances occurred. If fracturing or relief of pressure occurred because of tidal stresses or local weakness of the crust, and sufficient excess energy still resided in the rock, the evolution of gas from the magma-fraction and the heat of oxidation might cause the development of pressures that would exceed the strength of the overlying and surrounding crust. A series of explosions would result and the magma-hood would be largely destroyed by its own potential energy. The first explosion would cause immediate release of pressure upon lower parts of the magma-column within which the freezing factor approximated but slightly exceeded the value of the oxidation-factor, and this second quickly formed hood would explode in turn. This would continue until such depth in the magma-hood and column was reached that the forces were no longer able to disrupt the overlying crust or until the oxidizing factor became predominant when a considerable amount of remelting might occur. Lava might be extruded but quiet freezing would eventually be resumed. Release of pressure on this system might cause further rise of the magma since in the meantime more volatile oxidizing agents may become concentrated in the magma-hood, and another cycle of surficial volcanism would result. When the energy of the magma is no longer able to produce volcanic manifestations under the existing structural conditions, freezing will extend into the main body below and a period of mineralization will be initiated.

The question as to wherein lies this potential energy of the magma is answered to a large extent by the paragenetic history of ore-deposition itself. We have already seen that in the Ouray granodiorite a large amount of it lies in the low state of oxidation of iron in the magma.

but if we examine numerous other unconformities like that of hematite appearing in the sequence of ore-deposition in the San Juan Mountains and elsewhere we find two other elements, sulphur and manganese, for which there is direct evidence of the production of large amounts of heat by oxidation. We may suppose from the position of these three in the periodic table that nickel, cobalt, phosphorus, carbon, and others are of importance but their oxidation must occur chiefly at greater depths than those exposed in this region.

Without demonstration of the other unconformities and of their relations to each other, which would require much space, they are listed in tabular form as they appear in the early and later Tertiary mineral deposits of the San Juan region (see Table 4).

Table 4--Progression of unconformities downward in magma-hood as shown by sequence and zoning of ore-deposits on the western San Juan Region, Colorado

Unconformity	Principal reaction in magma-hood and source of heat-energy
Hematite	$Fe^{''} \rightarrow Fe^{'''}$, chiefly; $FeCl_3$ distilled from magma-hood
Manganese	$Mn^{''} \rightarrow \dot{M}n^{'''}$ (?), chiefly; $MnCl_{2-3}$ distilled from magma-hood
Fluorite	$S^{--} \rightarrow SO_3^{--}$, F liberated by action on fluorine-bearing minerals; Ca or CaF_2 distilled from hood
Barite	$S^{--} \rightarrow SO_3^{--}$, SO_3^{--} and Ba distilled from magma-hood

Note: Below the barite-unconformity, fluorite and possibly SiF_4 continue to be distilled. Heavier elements of Groups V to VIII are possibly oxidized, in addition to some Fe, Mn, and S. After this period of distillation, dominated by silica, adularia begins to form and a depth is reached at which two-phase transfer disappears or becomes feeble. The progression of single-phase ore-deposition between the unconformities is omitted from this Table, but will be discussed in a subsequent paper.

Relation to problems of igneous differentiation

The relationship of the fluorite- and barite-unconformities is believed to be especially significant, as much heat is generated at this unconformity, and the succeeding vein-sequence of the San Juan Area is featured by a great amount of silica that was selectively fused. Lindgren, in his recent paper in the volume on Ore-deposits of the Western States, lays great stress upon the significant distribution of fluorite in relation to barite and to the occurrence of alkaline rocks. The remainder of this paper will be taken up with outlining very briefly the relation of these different sources of heat-energy to problems of igneous rocks.

According to the mechanism presented all primary magmas may be produced by selective fusion initiated either by release of pressure or by some process of diffusion resulting in differential loss of hydrogen gas. Perhaps some other increment of energy may be operative under special conditions. In accordance with N. L. Bowen's (The evolution of the igneous rocks, pp. 315-320, Princeton University Press, Princeton, 1928) suggestion, we may consider perhaps that all basaltic magma results from selective fusion of the peridotite shell. As nearly all the rocks which we see in the Earth's crust, except meteorites, belong to this zone above the peridotitic shell it is not necessary to consider the deeper zones in this brief summary. H. S. Washington (Chemical composition of the Earth, Amer. J. Sci., Ser. 5, v. 9, pp. 351-378, 1925) estimated the composition of this shell based upon the composition of stony meteorites. His figures give 1.18 metallic iron, 15.86 ferrous oxide, and no ferric oxide. His figures for the basaltic shell, however, give 6.37 per cent FeO, and 5.38 per cent Fe_2O_3. It is probable, however, that this figure for ferric oxide is much too high because it is based upon the average composition of all basaltic magma which has reached the Earth's surface. Hence Daly's average compositions of olivine-diabase and plateau-basalt are probably somewhat more representative of basaltic magmas that have not been oxidized by extrusion, and these show an amount of ferric oxide slightly more than one-third that of ferrous oxide.

Except for this one discrepancy in the average figures for all basalt, however, we find that the ratio of ferric to ferrous iron mounts steadily in the normal subalkaline igneous-rock series ending with granite and rhyolite (see Table 5 and Fig. 3). In Figure 3 the change in ratio of ferric to ferrous oxide in igneous rocks as a whole is shown graphically by plotting the

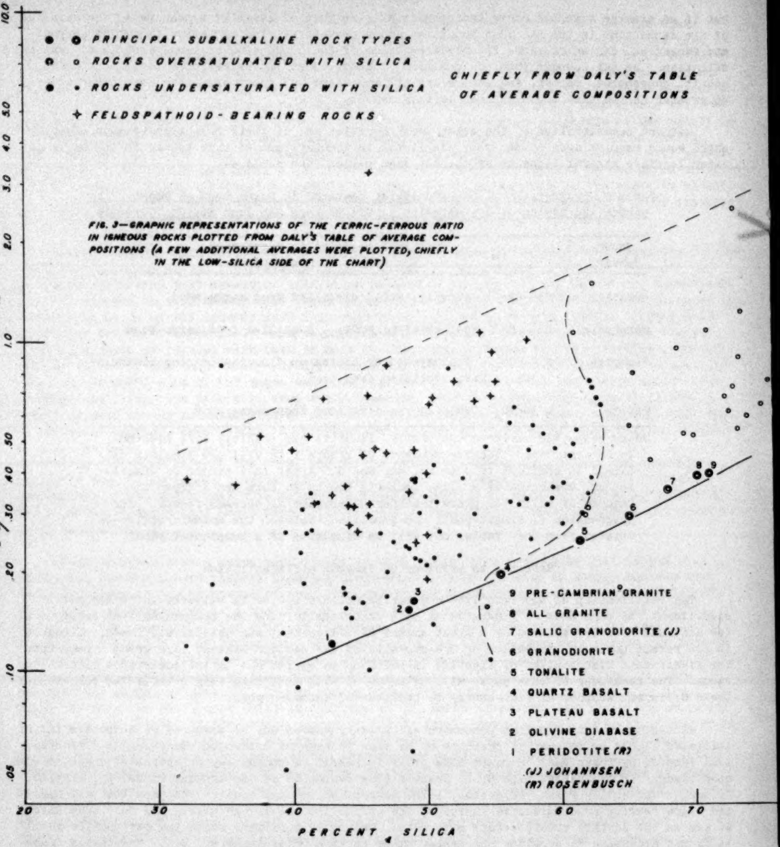


FIG. 3—GRAPHIC REPRESENTATIONS OF THE FERRIC-FERROUS RATIO IN IGNEOUS ROCKS PLOTTED FROM DALY'S TABLE OF AVERAGE COMPOSITIONS (A FEW ADDITIONAL AVERAGES WERE PLOTTED, CHIEFLY IN THE LOW-SILICA SIDE OF THE CHART)

logarithmic ratio of ferric to ferrous iron against the silica-content of Daly's average compositions. This change may be considered to represent a partial measure of energy expended in the formation of normal subalkaline magmas which have reached a position of equilibrium somewhere near the base of the fracture-zone in the crust. The rise of the magma-body through the crust may be presumed to involve several operations that are taking place simultaneously. First, a selective fusion of the salic material near the top of the magma-body or hood, accompanied by oxidation of iron together with small amounts of manganese, nickel, carbon, sulphur, and other elements of this series; second, the process of crystal-fractionation within the molten body; and third, the solidification along the base of the body as a result of its loss of energy. The hyperfusible constituents are thus continually acting as agents of energy-transformation near the top of the body as a consequence of this selective process. The role of crystal-settling in the differentiation-series of a rising magma-body with excess potential-energy is perhaps difficult to evaluate; we may picture it rather more as a moving liquid-body in a crystal mesh.

Table 5--State of oxidation of iron in igneous rocks and peridotite-shell of earth

Compound	Peridotite-shell[a]	Olivine-diabase	Quartz-basalt	Tonalite	Granodiorite		Granite	Rhyolite
					All	Salic[b]		
Fe	1.18	....						
FeO	15.86	8.88	4.86	4.29	2.65	2.18	1.78	0.88
Fe_2O_3	.....	3.06	2.13	2.39	1.74	1.75	1.57	1.45
$\frac{Fe_2O_3}{FeO}$	0.00	0.344	0.439	0.557	0.657	0.803	0.883	1.65

[a] H. S. Washington, The chemical composition of the Earth, Amer. J. Sci., Ser. 5, v. 9, p. 362, 1925.

[b] A. Johannsen, Descriptive petrography of the igneous rocks, v. 2, p. 331, Chicago, 1932.

All other analyses from R. A. Daly, Igneous rocks and the depths of the Earth, pp. 9-28, New York and London, 1933.

The production of alkaline magma by the body while moving slowly upward under conditions approaching equilibrium seems impossible, as the increment of energy is normally supplied only as fast as the body rises and the concentration of hyperfusibles increases the power of selectively dissolving silica at essentially the same rate as for potash. When a position sufficiently close to the Earth's surface is reached so that rocks very rich in alkalies may be encountered, the potential energy of the body is normally too low to result in appreciable assimilation.

Supposing, however, that a basaltic magma, because of strong crustal deformation or deep fissuring, is rather suddenly erupted to a position high above its normal level in the crust. Unless the release of pressure is sufficiently sudden or its final position close enough to the surface to produce vesiculation and loss of gas, rapid oxidation could not take place because of the lack of differentiation in its hyperfusible constituents. If, however, a release of pressure, whether by fissuring or deformation, affects a body in which hyperfusibles are already concentrated, oxidation will occur and even subterranean explosions might result. Normally the basaltic magma or any other parent magma which is raised high above its normal potential-level will first fuse its suspended crystals and further attack can only take place slowly along its contacts until crystallization allows further concentration of gases. Magmas with a high content of elements in a low state of oxidation and consequent high-potential heat-energy, which are within the range of open fissures in the crust, should, however, be among the more abundant of the effusive types. According to Daly's estimates of the volume of effusives, pyroxene andesite and basalt magmas, even though their sources lie much deeper in the crust than rhyolite, greatly exceed the latter in their combined volume of effusives.

A primary magma may be considered as any of these rising magma-bodies in a position near or above its normal level. Any primary magma, however, that is erupted very far above its normal level is a potential source of abnormal differentiates, providing crystal-fractionation can occur. The process of forming abnormal differentiates is similar to processes of mineralization, as Lindgren emphasized in his paper on differentiation and ore-deposition. The mechanism, which would be somewhat different from that of the decadent igneous body, may be applied to a primary magma that has been erupted to a position within the fracture-zone of the crust. The magma may become strongly differentiated by a combination of crystal-settling and selective fusion during crystallization. The potential sources of thermal energy in the magma thereby become unevenly distributed, tending to decrease below normal at the top and remaining much above normal near the base. As crystallization proceeds the oxidation-factor must finally exceed the freezing locally and, if momentary releases of pressure are provided, selective fusion will take place near those parts of the hood in which this relation exists. If the hood is sufficiently large and the magma-body near enough to the surface, violent eruption will again take place, but the erupted magma may, for example, be abnormally alkaline or siliceous, since the process of selective fusion has incorporated chiefly the later products of fractional crystallization. If, on the other hand, the magma-body is deep enough so that the crust is not disrupted, the differentiate will be forcibly expelled in a direction away from the more rapidly solidified parts of the magma-hood where the freezing factor was dominant, and a layer of alkaline or siliceous rock will be formed in the body. With continued loss of heat through the surrounding crust and by loss of expelled gases through the rock-pores, a new hood will start to form and the cycle is repeated.

If the excess potential-energy of the body is large enough and release of pressure is provided repeatedly, the magma could theoretically be completely crystallized and remelted. However, the loss of volatiles following each release of pressure probably is large, and if the body is enclosed in incompetent beds, the overlying rocks may be forced upward at each period of fusion, with the resulting concentration of volatiles near the top rather than below. Thus selective refusion, sinking of crystals, and fractional crystallization will tend continuously to concentrate volatiles in the upper parts of the magma until the hood begins to recede, or until the amounts of volatiles left in the magma are no longer able to induce fusion of the surrounding rock. The earlier products of refusion (the aplitic differentiates) have tended to desilicate the magma-hood and decrease its content of all salic materials, and as the hood is changing from transgressive to regressive phases no additional sources of salic materials are available. Hence, at the time of this changing phase of the hood the products of selective fusion will finally include certain critical differentiates such as the lamprophyres and other complementary rocks. It is possible also that certain of the monomineralic igneous types result from processes occurring at this change in phase of an igneous body.

Thus an igneous body in which there exists a high oxidation-potential is able to produce, by selective fusion complementary igneous rocks of many different kinds. If the magma is high in silica, rocks of the bostonite- or alaskite-type may be produced. If the body is zoned in depth or its average composition is not siliceous, then rocks under-saturated, with silica, will be formed, becoming gradually more femic during a change of phase, or as deeper parts of the body are remelted.

It is to be expected that differentiates produced from magmas in which a moderately large amount of heat-energy is suddenly released will commonly exhibit definite evidence of selective resorption and fusion of earlier-formed crystals that may be present. Crystals formed later during the final cooling of the liquid will, however, be in approximate equilibrium with the groundmass. The greater the thermal energy released the more extensive will be the effects of fractional resorption, but it cannot be presumed that such effects will merely revert the system to some previous stage of solid-liquid equilibrium. Immediately following the release of pressure, the temperature and pressure of the liquid magma-fraction is built up again to degrees that may greatly exceed those existing during the preceding stages of fractional crystallization. Thus the solid-liquid equilibrium will be shifted from its previous course a certain amount depending upon numerous factors difficult to evaluate. If the temperature builds up so rapidly that fractional resorption cannot maintain temporary equilibrium then a maximum shift from the previous equilibrium relations might be expected. Other factors that might subsequently affect the order of resorption in the mineral series would be the maximum temperature and pressure, the composition of the magma-fraction, the degree of fractionation in the solid crystals, the concentration of the hyperfusible constituents, and the composition of the material distilled from the fraction during the period of boiling. For example, under the conditions prevailing in the Ouray granodiorite ferrous and ferric iron seem to have been somewhat concentrated in the liquid fraction during resorption and similar phenomena appear to occur during the crystallization of basalt (C. N. Fenner, The crystallization of basalts, Amer. J. Sci., v. 18, No. 105, pp. 225-253, 1929) and the formation of certain trachytic magmas to be mentioned in later paragraphs. The degree of concentration of hyperfusible constituents may be an important factor in some of these processes, but speculation as to its effects is hardly justified when so little is actually known about even the qualitative trends of hydrous systems.

Magmas which have a lower reserve of thermal energy, or those in which the production of heat by oxidation is sufficiently slow to permit maintenance of approximate equilibrium during resorption, would commonly fail to exhibit strong departures from the normal fractionation or reaction-series. Also the effects of fractional resorption or assimilation under these conditions would hardly be distinguishable in the texture of the rock or its crystals. The system would thus trend toward the production of a normal differentiate of the particular magma involved, but the process would be hastened and the volume of the differentiate might be much increased if assimilation of foreign material lower in the reaction-series occurred. This particular trend of differentiation is that of normal crystallization represented by the reaction-series of N. L. Bowen (The evolution of the igneous rocks, Princeton University Press, pp. 54-62, 1928), and doubtless the bulk of the igneous rocks belong to this series (see Fig. 3).

The order of oxidation of elements in the igneous bodies of the San Juan Region show that sulphur is oxidized to its highest state only after the potential energy of iron that is locally available has been essentially exhausted. Thus the production of fluorite and barite, which Lindgren has shown to be intimately related processes, represents the oxidation of the sulphide-ion (S^{--}) to the sulphate-ion (SO_3^{--}).

Because of the large amount of heat generated and the selective fusion of compounds in the rock, much fluorine is liberated from minerals in which it has been previously combined. The reasons for the concentration of barium need not be considered here but this seems to result from the normal concentration of heavy elements in the magma-residues by the mechanism of the magma-hood. Thus alkaline rocks which are associated with fluorite come from magmas at the border-line between those of sufficiently high energy to produce greater volumes of alkaline magmas, and those whose energy level is low enough to allow the production of siliceous emanations and mineral deposits. As the energy of the magma becomes lower the volume of abnormal igneous differentiates falls and the volume of mineralizing emanations increases. Thus, as Lindgren has pointed out, the greatest concentrations of fluorite tend toward the eastern borders of the Rocky Mountain province where alkaline magmas are more abundant, whereas the greatest concentration of mineral wealth lies west of this zone in regions where the magmas entered their period of decadence with a lower reserve of heat-energy.

In a broad sense we may consider the two major groups of differentiates near the poles of a series of igneous processes. One pole represents the slow rise of igneous bodies in the deeper crust wherein a close approach to equilibrium is maintained throughout the span of differentiation. The products are those resulting from selective concentration of salic constituents in the rising magma-body and range from olivine-gabbro or diabase through quartz-basalt, tonalite, and granodiorite, to granite (see Fig. 3). The other pole is represented by the more wasteful processes of explosive volcanism wherein a large proportion of the potential energy of the magma is spent in external work not contributory to differentiation. This difference results naturally from the second law of thermodynamics that heat cannot be converted into work in surroundings of constant temperature. The nearer an igneous body approaches to the Earth's surface the greater is the opportunity for the rapid loss of volatiles with consequent greater rise in temperature of the body with respect to the surrounding crust. When these relative terms reach a certain value close to the Earth's surface the internal energy of the body is enabled to disrupt the overlying crust, and the energy is dissipated in breaking of the rocks and in expansion of gases. The processes of differentiation henceforth produce only minor igneous or mineralizing products of the decadent igneous body.

Production of trachytic magma from basalt, a quantitative example of heat generated by oxidation

In order to illustrate roughly the amount of heat generated by oxidation of iron and the adequacy of the heat to produce a given volume of differentiate, the production of trachyte from basalt may be taken as an example. R. A. Daly (Igneous rocks and the depths of the Earth, pp. 470-473, New York and London, 1933) gives analyses of trachytes and basalts from oceanic islands that may be used with some confidence regarding the origin of the trachyte.

Compound	Ascension Island basalt	Ascension Island trachyte
SiO_2	49.63	66.31
Al_2O_3	16.13	15.54
Fe_2O_3	4.02	3.49
FeO	7.47	1.15
MgO	5.35	0.27
CaO	8.78	1.08
Na_2O	3.70	6.42
K_2O	1.31	5.02

Whether or not the enrichment in alkalies characteristic of trachytes is entirely the result of crystal-fractionation or partly the result of selective fusion it may be supposed that the trachytic magma will contain the bulk of the potash present in the original basalt. It follows in the example above that the volume of the liquid trachyte produced is roughly one-fourth to one-fifth that of the partially crystallized basalt from which it was derived. The trachyte is relatively enriched in the oxides as follows: Potash, 4 X; soda, 1.7 X; silica, 1.3 X; alumina and ferric iron are nearly the same. The enrichment in potash, soda, and silica can be explained as the result of known processes of crystal-fractionation, but the lack of much change in ferric iron cannot be explained easily. If, on the other hand, the trachyte is derived by selective fusion under oxidizing conditions the relative increase of ferric iron with respect to total iron is not incompatible with the process. The fractional resorption of ferromagnesian minerals in igneous rocks provides numerous examples of the preferential attack of volatile-rich magma-fractions on these minerals as compared with the more calcic plagioclases. The enrichment of a superheated liquid in ferrous iron in preference to lime or magnesia is to be expected within certain limits of composition (C. N. Fenner, The Katmai magmatic province, J. Geol., v. 34, pp. 756-757, 1926).

The original ratio of selective fusion of FeO and Fe_2O_3 in the trachytic liquid is not determinable, though certain limits are set by the present composition of the trachyte. Thus not more than 3.14 per cent FeO could have been oxidized during the process, nor could more than 3.49 per cent Fe_2O_3 have been dissolved as such unless reducing conditions prevailed. If the same ratio of Fe_2O_3 to FeO in the basalt was preserved during separation of the trachytic liquid, then the amount of FeO oxidized to Fe_2O_3 during the process would amount to about 1.07 per cent. Probably, however, the exact amount of FeO oxidized was between 1.07 and 3.14 per cent, because of the preferential solution of ferrous iron. A mean value of about two per cent may be used to simplify the calculation.

In accordance with the conception that the process of oxidation usually takes place after sufficient magma has crystallized to provide a strong vapor-pressure, it may be supposed that approximately five to fifteen per cent of the basalt was in a molten state when oxidation took place. Thus out of 100 volumes of basalt ten to twenty volumes of liquid must be produced by selective fusion. The two per cent of ferrous iron in the volume of trachyte of specific gravity 2.6 will amount to about 5.2 grams of FeO oxidized.

The calculation of the heat produced by this oxidation is only an approximation because temperature- and pressure-effects will be disregarded, and also little is known about the actual mineral composition of the trachyte. The norms of the Ascension Island trachytes show from three to four per cent magnetite, but these figures are doubtless larger than the modal percentages. The magnetite in trachytes commonly occurs in scattered dust-like particles that are partly altered to hematite. The calculation will be made first on the basis of formation of solid hematite. The values given in thermodynamic tables for various oxidation-reactions of iron are:

$Fe^{''}$ ------------ Q = 20,600 cal/gm-mol
FeO (solid) ---- Q = 64,040 cal/gm-mol
Fe_2O_3 (solid) -- Q = 190,700 cal/gm-mol
Fe_3O_4 (solid) -- Q = 266,910 cal/gm-mol

If the amount of iron already in solution in the magma-fraction were known the free energy of chance from the ferrous ion ($Fe^{''}$) or from liquid FeO to solid Fe_2O_3 might be used to approximate the heat produced in the liquid fraction. However, all of the ferrous iron will be assumed to be in combination as solid FeO though the total heat produced will be somewhat less.

The oxidation equations are:

$$2\,Fe + 3\,O = Fe_2O_3 - 190{,}700 \text{ cal/gm-mol}$$
$$2\,FeO = 2\,Fe + 2\,O - 128{,}080 \text{ cal/gm-mol}$$

$$2\,FeO + 1\,O = Fe_2O_3 - 62{,}620 \text{ cal/gm-mol}$$

This is equal to 392 calories per gram of Fe_2O_3 produced, and 5.2 grams of solid FeO if oxidized would produce a total of 2250 calories. If the heat of fusion of the more readily fusible mineral molecules of the basalt is assumed to be about 50 calories per gram, the total amount of heat would fuse approximately 45 grams of minerals. With the density of the liquid near 2.5 about 18 volumes of trachyte magma could be fused from solid rock by this thermal energy. The heat evolved by formation of magnetite is about 323 calories per gram, so that if the solid FeO were all changed to magnetite 1800 calories of heat would be evolved and fourteen volumes of trachytic rock could be fused. These limits are close to the ten or twenty volumes required together with the amount of liquid assumed to be originally present in the basalt. Inasmuch as many assumptions were made for which there is no real justification in fact, this close correspondence may or may not be significant. There are doubtless many factors not susceptible to valuation, some of which increase and some of which decrease the amount of thermal energy that would be available for processes of differentiation. The equations used are probably not correct because chlorine gas may very likely take part in the oxidation-reactions. Also, as has been mentioned, a certain proportion of the thermal energy has been converted into work. This work is measured by the expulsion of the trachytic magma from its parent basalt and by the extrusive processes which may or may not include explosive phenomena. It must be emphasized, however, that the energy of the trachytic magma is partly contained in its intrinsic heat derived from the depths of the crust and that when the magma is extruded to the surface of the Earth this energy becomes partly available for the performance of work. The maximum amount of thermal energy that can be converted into work in a perfect heat engine is limited by Carnot's equation,

$$w/q = (T - T')/T$$

where T and T' represent the temperature within the body and those existing at the surface. Accordingly, when the magma is extruded to the surface, additional energy becomes available for the performance of work which is over and above the increments added by processes of oxidation. Unless we know the actual amount of work performed during extrusion and can balance this against the intrinsic heat-energy in the magma before oxidation occurred, we are unable to determine whether any of the work involved has actually reduced the amount of oxidation-heat available for processes of differentiation. It seems reasonable to assume, however, that a large proportion of the oxidation-heat was actually available for processes of differentiation, and that the remainder of the intrinsic energy plus some excess oxidation-heat was capable of performing the work of extrusion.

There are also certain other considerations which indicate that the available oxidation-heat may be much greater than shown by the calculations: (1) Other compounds may be formed which add to the increment of oxidation-energy especially if oxidation is considered in the broader sense of a change from a lower to a higher state of valence. Many trachytes contain sulphur trioxide in some combination and the heat evolved by oxidation of sulphur to a stable compound of this valence is very great. Many of the more easily volatilized elements that may form such compounds escape from the rocks during consolidation and their heat effect cannot be estimated. (2) Some proportion of the ferrous iron may be present in the residual liquids of the basalt both in the liquid and ionic condition. If part of the iron is changed to magnetite or hematite directly from these states the available heat-energy will be greater than that calculated for solid FeO. (3) Sufficient release of pressure to induce oxidation would result in the distillation of some ferric chloride from the magma-fraction, which would not be accounted for by the analyses of the solid rocks. Also a part of the oxidation-products might not be incorporated in an interstitial liquid which was separated from its parent rock. (4) The thermal energy stored in the liquid fraction is likely to be appreciably greater in proportion to the quantity of the liquid than that which remains in the solid basalt.

Some of these additional increments of available thermal energy may or may not offset certain endothermic effects caused by exsolution of gas from the magma-fraction and by heat required to separate the hydrogen and hydroxyl ions. The author is fully aware that the quantitative values of the various exothermic and endothermic processes involved in the proposed mechanism of magma-bodies are not at present determinable. If, however, we find consistent evidence in the igneous rocks that thermal energy exists in excess of that evolved during simple crystallization-differentiation, then we must assume some likely source of this energy, and oxidation-processes seem to meet these requirements. The mechanism here presented is offered as an hypothesis for testing against the observed facts of geology rather than as one which is demonstrated by thermodynamic principles.

Acknowledgments

The author is much indebted to many members of the Geological Survey for discussions of the problems involved, and especially to James Gilluly for critical reading of the original manuscript and other valuable suggestions. Also much help was rendered by the members of the chemical laboratory in discussions of problems and of the rock analyses which they made, and by R. C. Wells and H. C. Spicer in the discussion of thermodynamic calculations. P. G. Nutting contributed certain ideas regarding the geophysical conditions attending the oxidation of iron in the magma. C. S. Ross has also read the manuscript and given further helpful suggestions during the course of its preparation.

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ORIGIN OF ANORTHOSITE IN THE ADIRONDACKS AND IN GENERAL

A. F. Buddington

The relationships of the Adirondack anorthosite and associated rocks have been reinvestigated. The order of intrusion is interpreted as anorthosite, gabbro, quartz-syenite, diabase, granite, diabase (Keeweenawan). The evidence is clear that gabbro and quartz-syenite form dikes in anorthosite, and it is believed that they also show evidences of chilling against anorthosite. The anorthosite-magma has given rise to profound pyrometasomatic replacements of limestone country rock of a type peculiar to it. The metamorphosed rocks are locally injected by quartz-plagioclase veinings related to the anorthosite. All the phenomena are consistent in indicating formation of the anorthosite through differentiation from a gabbroic anorthosite-magma with a distinct content of volatiles. The hypothesis of a rest-magma of the composition of the quartz-syenite on the one hand, squeezed out from an anorthositic fraction on the other, does not satisfy the requirements of the new data.

Anorthosites in general occur as: (1) Large masses of domical structure, such as the Adirondacks, Laramie (Wyoming), San Gabriel (California), etc.; (1-a) as small sheets in outlying bodies related to (1); (2) as one of the major facies of stratiform noritic sheets, such as the Bushveld, Stillwater (Montana), etc.; and (2-a) as minor facies of gabbroic sheets or bodies. The plagioclase in eight out of ten bodies of the Adirondack Type, for which data are available, in only exceptionally more calcic than An_{65}, and in general An_{35-60}, whereas that in the stratiform-sheets is, except to a minor extent, always more calcic than An_{60}, and varies between An_{60} and An_{85}. If massifs of the Adirondack Type are the upper facies of a stratiform-sheet, some of them should therefore be expected to be bytownite, which is not the case.

Analogy with stratiform-sheets suggests the possibility that an anorthosite horizon consisting of bytownite and perhaps calcic labradorite may well be present above the peridotite shell in the interior of the Earth. Partial melting of such an anorthosite-shell or stratum would yield a gabbroic anorthosite magma of the requisite character for the Adirondack Type of intrusion, and would be consistent with the generally restricted composition of the plagioclase shown by such bodies. The restriction of anorthosite of this origin to the pre-Cambrian would find a natural explanation in higher temperatures, locally or as a whole, at higher levels in the Earth's crust at this period.

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SOME RECENT STUDIES OF SIERRA NEVADA PLUTON

Evans B. Mayo

(Abstract)

The intrusive core of the Sierra Nevada, California, is a composite mass, some 400 miles in length and locally more than 70 miles wide. In upper Jurassic time, it intruded intensely folded Paleozoic and lower Mesozoic rocks. It trends northwest, parallel to the coast. Structure-sections across this pluton have been surveyed by E. Cloos, near the center of the range (Yosemite Section), and in the north part (Donner Section). A third profile (San Joaquin Section), about 25 miles south of Yosemite, has been studied recently by Mayo.

This paper deals with two features of the pluton: (1) Northward plunge; (2) north-south, discordant trends along the eastern border. (1) E. Cloos's suggestion, that the pluton as a whole plunges northward, is borne out by a comparison of flow-structures on Yosemite and San Joaquin sections. On the former, flow-layers define broad domes, or arches, that indicate nearness to the roof. On San Joaquin Section, such domes are lacking, and their place is taken by steep-walled, irregular cylinders and funnels that suggest a lower level in the igneous body. (2) The discordant, nearly north-south axis of Tuolumne Complex, on Yosemite Section, is matched farther south by the abrupt northward bulging of intrusions that trend northwest. These discordant features show a barbed relation to the regional trend of the pluton, and they are accompanied by swarms of nearly north-south joints that differ from the usual northwest and northeast regional sets.

The Tertiary-Quaternary fault-pattern roughly follows the older structures. Northwest faults determine the general trend of the range, whereas northeast, and especially north-south, faults produce vast embayments in the mountain front. Most of the young volcanoes follow north-south en échelon faults or fissures. The fact that north-south en échelon structures have repeatedly localized the rise of magma indicates tension. Tension-fractures so arranged could have been produced by (a) torsion, or (b) horizontal shear as suggested in 1928 by Hans Cloos. It is concluded that (b) best fits the known facts concerning crustal motion in this region. Accordingly, northwestward migration of coastal areas began at least as far back as upper Jurassic time, and it may have controlled growth of the pluton.

The writer's contribution was made possible through grants from the National Research Council, and was aided by many helpful suggestions from Professor Ernst Cloos.

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TWO AFRICAN NEPHELINES

N. L. Bowen

(Abstract)

In order to determine the relationship between nepheline phenocrysts and the magma from which they separate, the chemical composition has been determined of nepheline from a soda-rich rock, phonolite, typical of the East African Rift, and that of a nepheline from a potash-rich rock, melilite-leucite nephelinite, typical of the Central African Rift. The two nephelines are, respectively, soda-rich and potash-rich and thus emphasize the variability of the composition of nephelines and its control by the magma from which they form. The results will be given in detail in a paper by Bowen and Ellestad to be published in The American Mineralogist.

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MODE OF INTRUSION OF PRE-CAMBRIAN GRANITES IN CENTRAL BOULDER COUNTY, COLORADO

E. N. Goddard

The manuscript for this paper was not submitted.

U. S. Geological Survey,
Washington, D. C.

SLOPES OF THE WALLS OF LUNAR CRATERS

F. E. Wright

The manuscript for this paper was not submitted.

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Washington, D. C.

SILICATE-WATER SYSTEMS: THE SOLUBILITY OF WATER IN ALBITE-MELT

Roy W. Goranson

Investigations concerning the problem of evaluating the stability relations of silicate systems containing volatile components are being carried out by the writer at pressures up to 4000 bars. The determination of the solubility relations of these systems is a necessary and important part of such a research.

Rock-forming silicates are, as indicated by the available evidence, miscible in all proportions in the liquid-state for the temperatures and pressures here considered. Any exceptions which have been established (J. W. Greig, Amer. J. Sci., v. 14, pp. 473-484, 1927; also v. 15, pp. 375-402, 1928) lie outside of this temperature-region. water is, on the other hand, very insoluble in rock-forming silicate melts even though the system be subjected to a high external pressure.

The solubility of water in the silicate-melt is not only a function of temperature and pressure but is dependent also on the particular solvent species chosen, that is, will vary with the composition of the silicate. Even though the absolute values of the solubilities are found to vary appreciably with the silicate-species, nevertheless the general trend of the pressure-water concentration-curves appears to be fairly well established. A hyperbolic equation which was found to be the most suitable for expressing the solubility relations of the system, granite glass and water (R. W. Goranson, Amer. J. Sci., v. 22, pp. 481-502, 1931), serves equally well to represent the data for the systems, albite-water, orthoclase-water, and some scattered determinations on other silicate mixtures. The expression is $x = p/(a + bp)$, where x denotes the weight concentration of water, p is the pressure in bars, and a and b are positive quantities which are constants for constant temperature and silicate-species.

The albite- and orthoclase-glasses were prepared synthetically to insure their purity and for them the writer is indebted to Dr. J. F. Schairer of this Laboratory. The technique and apparatus have been described in an earlier paper (R. W. Goranson, op. cit.). Proper precautions were taken to insure a slight excess of water in each charge in order to be certain that the glass would be saturated. This excess water present in the charge leached out some of the constituents of the silicate melt and therefore altered the composition of the glass, but the amount of this change is assumed herein to be negligibly small. This assumption is considered valid because the leached material was found to be present in such minute amounts that it has not been possible as yet to determine its nature. Some of it seemed to have optical properties consistent with a substance leverrierite, which is a hydrous aluminum silicate. The excess water was driven off by heating the charge at a temperature of 100° to 105°. The heating was interrupted at regular intervals in order to determine the correction for diffusion of water from the glass; this correction becomes appreciable at high water-concentrations. The charges were then ignited and the loss in weight noted. The weighings were made on a micro-balance sensitive to a thousandth of a milligram and therefore, in determining the solubility of water in albite-melt, special precautions were necessary because some of the leached material appeared to be hygroscopic and if considerable excess water were present in the original charge this would be made evident by a continuous increase in weight on the balance pan. The amount of vapor-phase was therefore kept as low as feasible.

The data obtained for the solubility of water in albite-melt at the temperatures (in Centigrade degrees) and pressures (in bars) stated are presented in Table 1. The number of determinations made at any one temperature and pressure is given in the third column. In the fourth column under weight per cent of water the values stated are the averages of the several determinations.

Table 1--The solubility of water in a melt of albite-composition as a function of temperature and pressure

Temperature	Pressure	Number of determinations	Wt. per cent of water	Deviation (obs. — calc.)
830	2415	3	8.4	-0.3
900	1007	2	5.8	-0.2
	1250	3	7.2	+0.6
	1450	2	7.4	+0.1
	1775	4	7.9	+0.2
	2815	2	8.9	±0.0
	3290	4	8.9	-0.1
950	660	2	3.9	±0.0
	800	1	4.8	±0.0
	1000	2	5.4	-0.3
	2725	1	8.0	-0.3
1000	520	2	3.6	±0.0
	1000	2	5.5	±0.0
	1220	3	5.9	-0.1
	1250	4	6.8	+0.7
	1700	2	7.0	±0.0
	2575	4	8.5	+0.4
	2985	2	8.5	+0.1
1050	300	2	2.8	+0.4
	500	2	3.2	-0.2
	1000	1	5.3	±0.0
	1600	1	6.7	+0.3
1100	1260	3	5.4	-0.1
	2380	4	7.6	+0.2
1200	1260	4	4.9	±0.0

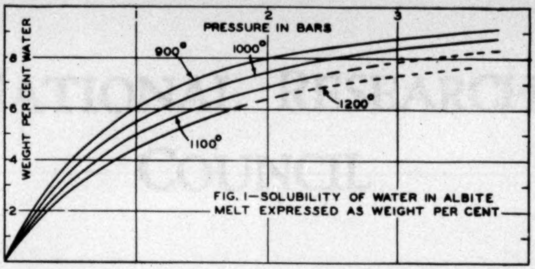

FIG. 1—SOLUBILITY OF WATER IN ALBITE MELT EXPRESSED AS WEIGHT PER CENT

The data presented in Table 1 are the values actually determined. In view of the fact that in making these determinations several different methods of analyses were used, each point was first given a probability weighting to accord with the particular technique employed and the least-square hyperbolas were calculated from the weighted values. It will be observed that the average deviation of these unweighted values from the values calculated by means of the hyperbolic equations given below is 0.2 per cent of water or, in other words, that the curves reproduce the measured values to an accuracy of within five per cent. Furthermore, the individual deviations show no particular trend.

The weighted least-square hyperbolic equations expressing these functional relations are

$$\begin{aligned} T &= 900°: & x &= p/(81.84 + 0.08458p) \\ T &= 1000°: & x &= p/(95.05 + 0.08715p) \\ T &= 1100°: & x &= p/(110.56 + 0.09008p) \\ T &= 1200°: & x &= p/(134.43 + 0.09100p) \end{aligned}$$

As above, x is expressed in weight per cent of water and p in bars. This family of curves is shown graphically in Figure 1.

The equation for $T = 900°$ approximates very closely to the expression obtained for the solubility of water in granite glass at 900°. The temperature-coefficient for the latter at 1000 bars is less, however, than that given here for albite-water, but the deviation is so small that it is not certain how much of the difference is real. Furthermore, the data would indicate that the temperature-coefficient of solubility is independent of temperature within the temperature interval 900° to 1200° and approximately independent of pressure for pressures exceeding 500 bars. The temperature-slope is so small, however, that these data would not make evident any except large deviations from linearity. This slope is important; hence, further work on a larger scale will be attempted in order to increase the accuracy of the measurements.

In the paper (R. W. Goranson, op. cit.) previously cited it was found that water is less soluble, by about one per cent, in a 25 quartz-75 orthoclase-mixture than in granite glass. It was found that approximately the same relation holds between orthoclase and albite-melts, the difference in water-content being from one to 1.5 per cent; the temperature-pressure-water concentration relations obtained for albite could be evaluated only in part for orthoclase because in the latter system the crystalline leucite phase is present except at high pressures (R. W. Goranson, unpublished work).

The solution of water at the temperatures considered here is an exothermic process, that is, is accompanied by an evolution of heat. This heat given off on solution increases with temperature but decreases with pressure, for example, at a temperature of 1000° and pressure of 2000 bars a rise in temperature of 100° would be approximately nullified by an increase in pressure of a thousand bars. At higher pressures more, and at lower pressures less increase in pressure would be needed to nullify the effect of this rise in temperature on the heat of solution. Conversely the evolution of water-vapor from a granite magma would be accompanied by an absorption of heat from the magma and the amount of heat absorbed is approximately as given in the earlier paper cited. Further details on this phase of the problem will be presented in a paper dealing with the freezing-point diagrams of these systems.

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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION

SEVENTEENTH ANNUAL MEETING
APRIL 30, MAY 1, 2, 1936
WASHINGTON, D. C.

WEST COAST MEETING
JANUARY 31 AND FEBRUARY 1, 1936
PASADENA, CALIFORNIA

PART II

REPORTS AND PAPERS
SECTION OF HYDROLOGY
AND
WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1936

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ANNUAL REPORTS OF PERMANENT RESEARCH COMMITTEES FOR 1935-36

REPORT OF THE COMMITTEE ON SNOW, 1935-36

J. E. Church, Chairman

Organization

The personnel of the Committee on Snow was chosen to represent not only districts and large watersheds but also phases of interest. These phases dealt originally with the forecasting of water-supplies in lakes and streams. But this basic Western interest quickly expanded into general snow-studies, ice-engineering, alimentation of glaciers, and polar exploration; then into snow-removal, flood-forecasting, and the conservation of snow. The present year two additional phases have been discovered, namely, (1) international forecasting and distribution of streams and (2) winter sports. The former was developed by W. A. Lamb and O. H. Hoover, district engineers in charge of Federal Water-Resources Divisions in Montana and Alberta. The latter should be credited to the National Parks Service.

Progress

Progress has become more rapid than ever and is evidently permanent. The Colorado River Project is nearing completion. The projects on the Missouri and Columbia are steadily advancing. The Great Valley Project in California has now been formally begun under direction of the United States Bureau of Reclamation. The first forecast for the upper Missouri has been made by the Corps of Army Engineers. An experimental forecast-system for the upper Colorado has been put into operation by the United States Bureau of Reclamation. A flood-forecast service has been perfected by the United States Weather Bureau on the Columbia.

But overspreading and uniting all systems are the Federal-State Cooperative Snow-Surveys now authorized for the Western States by act of Congress and placed in charge of the Division of Irrigation of the United States Bureau of Agricultural Engineering. The snow-survey broadcasts inaugurated by the Committee on Snow have been transferred to the Division of Irrigation and are awakening public consciousness in snow and water. An integral part of this movement is the report of the National Resources Committee urging the "course-method" of snow-surveying already used in several of the Western States and a trip by the Chairman of the Committee of Snow during last summer to practically all of the Western watersheds of the United States and Canada.

The unprecedented floods in the East covering fourteen states and the resulting authorization by Congress of flood-prevention projects should add further impetus to snow-surveying as a basic method of determining potential flood-conditions.

The International Commission of Snow organized in 1933 at Lisbon, is now approaching its first conference at Edinburgh. The members of the Commission will exceed 100, so great is the interest, and the three days of September 14-16 preceding the formal opening of the International Association of Scientific Hydrology have generously been set apart for the large program. Proposal has already been made that the Commission of Snow be expanded to include all forms of snow and ice and thus conform to their organic unity.

Regional reports

Greater details are given in the following regional reports based largely upon the Chairman's visit to the Western watersheds and the observation of others in close touch with conditions.

New England

In addition to the snow-survey system conducted in the Androscoggin Basin by the Union Water-Power Company of Lewiston, Maine, there should be noted the Connecticut River Snow-Survey covering the entire Connecticut River System and particularly the White Mountains. This work is conducted by the Connecticut River Development Company, Boston, Massachusetts.

The heavy snow-cover with even heavier rains of March has produced a surfeit of water throughout all the Eastern States. Dr. Charles F. Brooks, Director of Blue Hill Observatory, Milton, Massachusetts, describes the condition graphically:

"The recent heavy rains, over 20 inches in eleven days at Pinkham Notch, on 48 inches of snow produced numerous slush slides and avalanches, one of which crushed a house and killed its lone occupant. The snow melted from 48 to 19 inches in less than two weeks, the strong southeast wind which brought the tropical moisture that made the rain also melted the snow at high speed. The maximum wind on Mt. Washington was 186 miles per hour (subject, possibly, to reduction for lift-error of the heated anemometer) from the southeast. This same wind went far inland, yielding heavy snows as far west as Buffalo (19.5 inches March 17) and later heavy rains over the northern and north central Appalachians starting a great flood in western Pennsylvania. Buffalo's snow largely held till a few days later another ten inches was dumped on top of the old. The heavy snow-cover in central New York is now going out on a warm wave, making floods there. Some times we are having in these parts! The floods of the great rivers heading in the Mt. Washington mass were the maximum known, and created enormous havoc. In Springfield, 175 city blocks went under, and when the waters receded the streets had to be plowed with snow-plows."

New York

The condition referred to by Director Brooks and the plan of Congress to create a system of detention-dams caused Robert E. Horton, Consulting Hydraulic Engineer, of Voorheesville, New York to write as follows:

"Another topic which I wish might receive consideration is the relation of snow and ice to floods. This topic is particularly pertinent at the present moment, as we have had here in the East two severe floods during the month of March, the first of which was occasioned at most places by a combination of excess of ice and lack of water. The second was a normal flood, after ice and snow were gone, resulting entirely from rainfall. I had heretofore noted occasions of severe floods from ice-gorges due to lack of water adequate to wear away and carry out the ice as it broke up--in fact, withholding of large volumes of water in storage-reservoirs at the head-waters of a stream may apparently, in some instances, intensify ice-gorge floods in this way. I wish this whole subject might receive adequate consideration."

Northern Continental Divide

The Northern Continental Divide embracing Montana-Idaho is so completely the chief source of runoff for the upper Missouri and upper Columbia that the two streams can well be joined in a single snow-survey system straddling the Continental Divide. However, the Missouri below Fort Peck and the Columbia below the Dalles would lie in divergent precipitation-zones. Furthermore, these sources center to a large extent in the limited area of Yellowstone and Glacier National parks. The only exception is the Upper Columbia which rises in the Canadian National Parks just over the Boundary.

Here, too, is the international St. Mary River flowing from Glacier National Park into the Canadian Saskatchewan.

Despite the large effect of summer rain upon the runoff, the first forecast based upon two seasons of snow-surveys has been unusually close. G. H. Hathaway, Committeeman for this Division writes:

"The relationship of the flow of the Missouri during the April-July runoff-period, with respect to the normal flow over a period of 25 years, has been determined. We made a forecast that the runoff would be 55 per cent of normal. The actual flow was 49.6 per cent. I consider the results very good, in view of the fact that we only had information for two years on the water-content of the snow in storage on March 1. A value was actually determined for the normal water-content of snow at the different courses."

Southern Continental Divide

The Southern Continental Divide embracing Wyoming-Colorado is a more important source of water than at first thought and snow-surveying is essential to the economic welfare. From the eastern slope flow the upper Platte and the Arkansas; from the southern, the Rio Grande; and from the western the Green, Colorado, and San Juan combining to form the lower Colorado now under storage-control. Storage-projects are under way in this Region and water is being transferred by tunnels to the scantier eastern streams. During the drought the users of water east of the Divide demanded forecasts of water-supplies before venturing to plant.

Despite its rugged mountains and reputation for avalanches, Colorado is ideal for snow-surveying. Transcontinental railways, National Parks, National Forests, and storage-projects afford easy accessibility throughout the winter to a parallel set of snow-survey courses spanning the length of the Divide. Lower outpost-courses are also accessible though possibly at somewhat greater effort. Avalanche-regions are relatively few and can be avoided. Thus the last barrier to snow-surveying falls away.

Furthermore, three-fourths of the runoff of the Green River, the northern tributary of the Colorado, comes from the states of Colorado and Utah and nine-tenths of the total flow of the lower Colorado comes from above Colorado's southern boundary. It is obvious, therefore, that Colorado-Utah are key states in snow-survey forecasting for this stream. The United States Bureau of Reclamation had even planned a still smaller area for establishing an experimental precipitation and snow-survey system for forecast-purposes. Ralph L. Parshall of the

United States Division of Irrigation reports "The public interest exceedingly encouraging."

Eastern Great Basin

To the Chairman, Utah was impressive for the endurance of its streams and the frugal use of its water, whereas Wyoming seemed to make little appropriation of the Green River, which may ultimately be diverted to some extent into the Bear River which belongs jointly to Wyoming, Utah, and Idaho. The impression was immediate and strong that Wyoming raised cattle and Utah homes.

Western Great Basin

Because of the momentum gained from its pioneer work in snow, Nevada continues its research in connection with its snow-surveys, though progress is slow because of present scarcity of funds. Cooperation is wide. Additional snow-courses on the headwaters of the Humboldt have been made possible by the construction of shelter-cabins. The excessive snow of the present season will not only comfort the water-users but will provide additional data for research, unfortunately long confined to subnormal flow.

Storage is now being provided by the United States Bureau of Reclamation on the lower Humboldt and upper Truckee. On the latter stream more detailed forecasting is contemplated to attain maximum regulation.

California

The following detailed report has been received from Harlowe M. Stafford, Regional Committeeman for California:

"The California Cooperative Snow-Survey as a State activity was resumed in September, 1935, an appropriation for this purpose having been passed at the 1935 session of the California Legislature. During the period from June, 1933, to September, 1935, there was no State money to carry this project but due to the fact that many of the cooperating agencies continued to make the surveys, using the State equipment permitted to remain in the field, the loss of records was not as great as might have been anticipated. Although the present appropriation is only about one-half of the former amount, the project has been re-established in good shape with greater contributions in some instances on the part of the cooperating agencies. The records now being obtained and the scope of the work are, therefore, not far below the former program. An additional item of cooperation which has meant considerable in the re-establishment of the work is that the Bureau of Agricultural Engineering, United States Department of Agriculture, has through Federal authorization and appropriation become the Federal agency to establish, correlate, standardize, and cooperate on snow-surveys in all of the Western States.

"Recent activity has called for considerable work in bringing all records, normal compilations, etc., through the period of State inactivity and up to date. This is nearly completed and with monthly surveys at key snow-courses at the end of January and February of this year, publication of the monthly bulletin of snow-survey and precipitation data has been resumed. Subsequent to the survey of all courses (about 170) at the end of March it is anticipated that all data and compilations will be in shape so that the annual forecast of streamflow for all of the major stream-basins of the Sierra can be prepared and published.

"The present outlook for the 1936 runoff is very favorable."

An analysis of the snow-survey reports received indicate that at the higner elevations the snow-pack is the best since 1932 and that in general the April-July runoff will approximate very nearly the normal runoff for the past 46 years. Incipient floods occurred during the heavy precipitation of February but the mild temperature then prevailing raised the elevation of the snow-line and thus gave assurance against later floods from a combination of low-level snow and rains.

The decision of the Federal Government to undertake the Great Valley Project will assure control and better distribution of the waters of the Sacramento and San Joaquin to the total region.

Southwest

The major problems of the lower Colorado are silt and transpiration-losses. The silt comes from the breaking down of the shale-formation thus creating the Grand Canyon and its many fingers and will continue as long as the Grand Canyon itself. The wide plain of the Little Colorado has not yet begun to erode though the vegetative cover is very sparse. However, this narrow margin of safety should be safeguarded and if possible increased.

The computed loss of 1000 sec-feet between Boulder Dam and Yuma is obviously due to the wide flood-plain filled with tules and bamboo between Topock and Yuma. It is possible that the control of the River may narrow the channel and thus reduce the area of the present evaporation- and transpiration-surface.

The Kaibab National Forest on the north and San Francisco Peak on the south will furnish minor snow-survey areas in connection with precipitation-measurements along the Colorado.

The most important snow-survey areas in Arizona-New Mexico are the White and Blue mountains which supply the Salt, Gila, and Little Colorado with practically their entire flow. Both the Salt and the Gila cease for practical purposes in Central Arizona and below their junction near Phoenix become merely a channel for occasional but destructive floods. The Rio Grande has its major source in Colorado, but minor sources lie also in northern New Mexico. Snow-surveys on all these streams are very feasible and at one time surveys were actually maintained at the head of the Salt River.

Pacific Northwest, especially Lower Columbia

Oregon is fortunate in having its stream-sources confined to two main areas, both easily accessible, the Cascade Range and the Blue Mountains. The former supplies the Deschutes, Willamette, Umpqua, and Rogue. The latter in northeastern Oregon supplies the Wallowa, Umatilla, and John Day. The Owyhee, however, rises on the Oregon-Nevada border and is forecasted in connection with the Humboldt River, Nevada, its southern neighbor, which shares with it the Charleston-Independence Range. The problems of forecasting in eastern Oregon as in eastern Nevada are the shallowness of the snow and the low altitude which may cause early melting.

New cooperators in the Oregon area are the United States Bureau of Reclamation in the Owyhee Basin and the United States Division of Irrigation in the Rogue. In the former basin topographic survey-sheets are being made by the United States Geological Survey. For the better regulation of Bonneville Dam the United States Army Engineers have entered into close cooperation with the United States Weather Bureau in the establishment of river and precipitation-gages on the Columbia. However, snow-surveying which should indicate the total flow of the stream and conditions potential to flood has been left to the United States Bureau of Agricultural Engineering.

Pacific Northwest, especially Upper Columbia

The Upper Columbia comprises three somewhat diverse areas, namely, the Snake River Basin, Clark's Fork and Spokane, and the Upper Columbia.

On the Snake River and its tributaries irrigation has long been practiced and snow-surveys have been conducted at Jackson Lake by the United States Bureau of Reclamation since 1919. Two men, Markham and his successor Hill, have had a continuous service of 17 years. Regarding the snow-survey, "Twin Falls wouldn't be without it," said Hill. In 1935 the error in the forecast was "possibly 40,000 acre-feet in 700,000 or six per cent." The Boise Area is served by a separate survey.

Clark's Fork is well adapted for snow-surveys since 60 per cent of its total flow comes from the three forks of the Flathead River in Glacier National Park. An additional 20 per cent comes from the Upper Clark's Fork, the Blackfoot, and the Bitterroot, where forecasts will aid irrigation as well as power.

The Upper Columbia is a Canadian stream but ultimately enters the United States in capacity three times as great as Clark's Fork. A great control-works at Grand Coulee is now under construction by the United States Bureau of Reclamation. If completed to maximum height the reservoir will extend upstream to practically the Canadian Boundary and will provide so much storage that it will be feasible to pump the water into the Grand Coulee for delivery to 1,225,000 acres of arid land reaching far down into the bend of the Columbia at Pasco where the Snake and Yakima enter the stream. With the Yakima Project it will take a large portion of the aridity out of Washington. The reservoir will be 151 miles long and can store approximately 5,000,000 acre-feet of water which will be released at low river-stages during the winter.

Forecasting for the Yakima Project has long been carried on by means of precipitation-gages at the reservoirs under joint cooperation by the United States Bureau of Reclamation and the United States Weather Bureau. Studies are now under way to determine the amount of refinement possible in the forecast by surveying the residue of snow on the watershed at the beginning of major runoff. Possibly the precipitation is mainly snow and the snow-cover is sufficiently heavy to absorb the occasional rains. Snow-surveys are conducted by the Washington Water Power Company in the Chelan River Basin on the same Divide.

E. H. Collins, District Committeeman, reports that, "The Washington Water Power Company has resumed snow-surveys this year both in the Spokane River Basin and the Chelan River Basin" and encloses a comparison of the annual snow-surveys in the Bitterroot Mountains since the surveys were begun in 1921. The record is complete except for the years 1933, 1934, and 1935 when only very fragmentary surveys were made.

British America

In British America, as in the United States, activity in snow-surveying extends over the breadth of the Continent wherever mountains or low temperatures furnish snow-storage.

Some snow-survey courses are maintained by British Columbia on the Upper Columbia. During the visit of the Committee Chairman last summer a complete snow-survey system was laid out for this Basin, except on the Canoe River, the northernmost feeder of the Columbia. This survey-system embraced the Kootenay, Upper Columbia at its source, and the Kickinghorse, all rising in the Rocky Mountain Watershed opposite the Bow which flows into the prairies of Alberta. A few well-placed snow-courses would doubtless be sufficient to afford a basis for forecasting all of these streams. An inspection of the Bow River Basin revealed continuous forests where drifting snow could be avoided and where the altitude and latitude combined should preserve the snow-storage unimpaired throughout the winter. A snow-survey system had been laid out in the Bow Basin as early as 1916 but was soon abandoned.

However, the international snow-survey and forecast system on the St. Mary River, established almost as early under the United States Geological Survey (Water-Resources Branch) and the Dominion Water Power and Hydrometric Branch, has been maintained until the present time and stands as an ideal example of international trust and cooperation. This stream supplies the Lethbridge Project of 130,000 acres in Alberta--a large project for so small a stream, but the rainfall is nearly ample without irrigation and the soil is close.

In eastern Canada in the St. Lawrence Basin results from snow-surveys are still inconclusive, as explained by M. Balls, Canadian member of the Committee:

"I am sorry I have been unable to report on the progress of snow-surveying in eastern Canada, mainly for the reason that, apart from Gatineau Power Company and ourselves, no systematic surveys of snow-cover are being made for the purpose of forecasting runoff.

"As for the two power-companies, I understand the Gatineau Power Company is maintaining its annual survey but has been unable to establish anything approaching a definite relationship between the water-content of snow-cover, as measured in March, and the resultant spring runoff. Our own experience has been somewhat similar excepting that, for the first two or three years, our attempts at forecasting gave fairly close results after adjustments had been made for departures from normal precipitation during the particular runoff-period.

"During the last few years, forecasts based upon snow-surveys have been wide of the mark, probably due to the effect of unknown factors such as ground-conditions prior to the 'freeze-up' and unseasonable thaws and rains during the winter.

"Until further study has been given to the various factors which have affected past forecasts, it would be premature to predict the attainment of definitely practical results. While other matters will keep me fairly busy this summer, I hope to be able to devote some time to the study of the problems I have mentioned and will give you a résumé in due course."

From west central Newfoundland, site of a snow-survey system of the International Power and Paper Company of Newfoundland, Inc., comes news of a severe flood in late January, due to ice-jams, which caused serious damage to a sluice-gate and pipe-line. This flood antedated by a considerable period the heavy floods in the East.

Western water-supply prospects

The Annual Broadcast of the outlook for irrigation water-supplies in the Western States forecasted a plentiful supply in general with some below-normal supplies in isolated sections of California and Utah. Reports from Texas indicate subnormal precipitation to date.

Conservation

The project of the California Agricultural Experiment Station on the influence of different kinds of forest-cover on the accumulation, density, evaporation, and melting of snow at elevations between 5000 and 6300 feet in Tuolumne County is now bearing fruit. The following report by the project leader, Professor Kittredge, and representative of Conservation on the Committee, seems to sustain the conclusions of the Nevada Agricultural Experiment Station for the Lake Tahoe Basin:

"As to my project on the relation of forest-vegetation to the evolution of the snow-cover the following paragraphs summarize its status.

"Records at the 100 observation-points under varying conditions of forest-cover at elevations between 5000 and 6300 feet in the Stanislaus River drainage in California are being continued for the third season by the Division of Forestry of the University of California. The evidence is accumulating that dense forest-cover by intercepting considerable portions of the snowfall reduces the total snow-accumulation and that an open forest where the openings between the trees or groups of trees approximate the height of the trees gives the maximum accumulation.

"A comparison of the water-equivalents of fresh snow on snow-boards and in a standard rain-gage (eight-inch) without the funnel illustrates the doubtful reliability of the rain-gage as a means of measuring snow. In 11 storms the total water-equivalent, averaged for five snow-boards, was 15.35 inches and for the rain-gage, 13.04. The ratio of gage to snow-boards was 0.85. Individual storms gave ratios varying from a minimum of 0.57 to 1.15.

"The evaporation-records from pans filled with cores of snow showed a rather consistent loss by evaporation during the daytime-periods, which was nearly balanced by gains by condensation during the night-time periods. The net result in this area seems to be a very slight excess of evaporation."

Winter sports

The bulletins on snow-conditions in the National Parks are turning the thoughts of mountaineers to winter sports and the best areas and times for pursuing them. These bulletins are now becoming radio broadcasts associated with the snow-surveys. The following bulletin is illustrative:

"Lassen Volcanic National Park, March--A greater amount of snow is now present on the ground at Lake Helen, at the base of Lassen Peak in this Park, than at any similar period in recent years, according to the snow-survey measurements compiled by Eugene J. Barton, park-ranger, after his monthly snow-survey and ski-patrol trip of the Park area.

"Barton revealed that there was a total depth of 195.7 inches of snow on the Lake Helen Course, which is situated at an elevation of over 8000 feet, with the present pack containing the high water-content of 80.2.

"The presence of the heavy pack in the high country of the Park insures sufficient snow for continued winter sports until late in the present season. Last year, skiing was enjoyed in the Park until late in July, and the present season was started in October when an early storm provided enough snow for ski-enthusiasts to enjoy their favorite sport.

"With the approach-road to the Park expected to be reopened shortly to public travel, spring skiing promises to be one of the major attractions of the Park during the coming months."

Equipment

Special attention has been given by the Nevada Agricultural Experiment Station the present year to lessening the weight and increasing the accuracy of snow-sampling apparatus. Duralumin, first suggested by Professor George D. Clyde, has proved sufficiently tough for shorter samplers but has not yet been tested for lengths of 12 to 24 feet. The tendency for the material to bend under construction can easily be corrected after the sampler-tubes have been completed. All of the earlier features of the "Mt. Rose" sampler have been retained except that the couplings and driving wrench are made of duralumin.

A satisfactory standard length for the sections is difficult to find, owing to the variation in conditions of distance, topography, and forest-cover. The present choice varies from 2-1/2 to 4 feet. A test must still be made of the relative obstruction to driving caused by many couplings. The bulbous cutter, recently devised to enlarge the hole to the diameter of the couplings, catches when the sampler is withdrawn and must be tapered. The original cutter is probably best. Because of the unpleasantness of oxidation, the duralumin should be coated with valspar varnish as in the case of the steel sampler.

Since duralumin is easily damaged by an open flame, it may prove necessary to abandon the plan of expanding the tube to insert the cutter and substitute for it the more doubtful method of solder-rivets. A thin-walled but rigid steel sampler may still prove the more satisfactory.

A careful test of the "Mt. Rose" spring-balance indicates that it possesses both sensitiveness and range, lacking in the cylindrical spring-balance. It is sufficiently sensitive to weigh the short duralumin tubes and shows only slight error in weighing the 20-foot sampler of duralumin or steel. It is thus universal and likewise possesses an adjustable index. The cylindrical balance tends to bind through friction both from the telescoping tubes and the freezing of moisture upon it. It also can not be readily fitted with an adjustable index. Its only advantages are its compactness and low cost.

A springless balance is now being perfected by John C. Stevens, Portland, Oregon, for weighing evaporation-pans in the field. Its central feature is its accuracy, provided sufficient protection can be afforded against air-currents.

Arctic

Dr. William H. Hobbs, Committeeman for the Arctic, is now completing his Life of Peary. Growth and ablation of glaciers are now being studied in Spitzbergen.

Antarctic

The great achievement of the year is the flight with occasional stops for observations of Lincoln Ellsworth and his pilot across the Antarctic Continent.

The Federal-State Cooperative Snow-Surveys

Built upon the foundation of the State Cooperative Snow-Survey systems of Nevada, Utah, California, and Oregon is the Federal-State Cooperative Snow-Surveys established by act of Congress with an initial appropriation of $15,000. Authority was given to the United States Bureau of Agricultural Engineering acting through its Division of Irrigation to cooperate with all agencies now engaged in snow-surveying, to coordinate so far as possible the work of all agencies, and to fill in gaps and set up such new courses as may be necessary and, in so far as funds will permit, to make the forecast cover the arid region.

The snow-survey system has now been extended from the four original states to Idaho, Montana, Wyoming, and Colorado, and the first snow-surveys have been made.

The mentor in the work is the Water-Resources Committee of the National Resources Committee which has now issued standards and specifications for hydrologic data. The "course-system" established by Nevada has been recommended, and also the "Mt. Rose" type of snow-sampler and spring-balance with an adjustable index.

Broad cooperation is being established not only with the states and their cooperating units but also with the National Forest Service, Park Service, Bureau of Reclamation, Army Engineers, Geological Survey, and Weather Bureau. The specific cooperation of the Geological Survey will be in stream-flow measurements and that of the Weather Bureau in measurements of precipitation and temperature.

For the present, seven regional headquarters have been established. Regional broadcasts of a local nature are issued in each district and a Central Broadcast is issued from the headquarters of the Division of Irrigation at Berkeley, California, covering the entire West. The basic snow-survey data with general forecast will be printed by the Section Directors of the Weather Bureau as a part of their Climatological Data.

In addition to the actual measurements and forecasting, it is the purpose of the Division of Irrigation to establish, as soon as funds are available, two or more research headquarters for the purpose of investigating methods, equipment, etc., and also factors affecting snow-surveying and irrigation water-supply forecasting. The State agricultural experiment stations of California, Nevada, Utah, Colorado, and Montana have already organized projects of this character.

Application has already been made to Congress for an annual appropriation of $50,000 to give the snow-surveys adequacy and stability. The feeling of the National Reclamation Association is voiced in the following resolutions passed at its convention at Salt Lake City, November 15-16, 1935:

Resolution No. 1

"WHEREAS, Agriculture of the arid region is dependent almost wholly upon irrigation, and

"WHEREAS, Water for irrigation is derived largely from melting snow, and

"WHEREAS, It has been demonstrated that the forecasting of the season's water-supply for irrigation from snow-cover measurements is of inestimable value in the planning of the season's crop-planting program, which is dependent upon the water-supply available for irrigation, now, therefore, be it

"RESOLVED, That that work of the Bureau of Agricultural Engineering in forecasting the irrigation water-supply through snow-measurements be commended and that the National Reclamation Association assembled at Salt Lake City this 16th day of November, 1935, endorse this work and recommend suitable Federal and State support for its continuance, and be it further

"RESOLVED, That the Bureau of Agricultural Engineering be requested to make its findings as to water-supply available as speedily as possible to water-officials in arid states where irrigation is practiced, and through them to water-users generally for their immediate benefit, and be it further

"RESOLVED, That a copy of this Resolution be sent to the Congressional Delegations of the Western States."

Resolution No. 5

"WHEREAS, In the arid region water is the key to land use, and it is important for long-range planning that adequate basic data be available as to water-resources, now, therefore, be it

"RESOLVED, That this Association urge that sustained studies of the water-resources of the Western States be undertaken by the proper Federal authorities to cover (a) ground-water conditions, (b) stream-flow and its possible utilization, (c) precipitation-trends as indicated by sustained historical records and tree-ring studies, (d) snow-surveys, (e) readjustment of water-rights to secure a more efficient use of water, (f) adjustment of crop-acreage, and (g) use of water on individual crops and lands from the standpoint of greatest returns to the district, and be it further

"RESOLVED, That this Association endorses the action taken by the Western States Engineers Conference in urging the continuation of the present water-resources investigational program of the United States Geological Survey."

Similar resolutions were also passed by the Association of Western State Engineers at its meeting preliminary to that of the Reclamation Association.

The Snow-Survey Bonus

Following a precedent of many years of paying snow-surveyors a bonus above their current wage to assure the most energetic effort in securing the desired data, recommendation was made by the Chairman to the United States Department of Agriculture that permission be granted to pay a similar bonus to the Forest Rangers upon whom the burden of making snow-surveys under the expanded system would fall, for most of the new snow-survey courses would be situated in the National Forests, where the streams have their source.

This was particularly desired in order to make it possible for the ranger to employ substitute aid in case of physical unfitness at any time to perform the strenuous work required. Because of the possibility of proposing a bonus for other types of hazardous work, an agreement was reached whereby the ranger should accept full responsibility for directing snow-surveys but should be provided with a cooperative fund for employing necessary labor. Where local labor is not available, it would be permissible to bring in younger employees of the Forest Service, if necessary, to perform the work.

These might receive additional compensation for such special work. A local employee list of properly qualified men subject to call by the Forest Service has already been started and has received the full approval of the Assistant Chief of the Service.

This solution of the problem is probably best, for cooperative projects generously accepted by the Forest Service can easily outgrow the personnel available to conduct them.

Western Interstate Snow-Survey Conference

Two sessions of the Western Interstate Snow-Survey Conference were held during the year. One of an informal nature was held at Salt Lake City, November 16, 1935, in connection with the National Reclamation Association to discuss snow-survey methods and Federal cooperative plans with Montrose W. Hayes, Chief, River and Flood Division of the United States Weather Bureau. Some twenty representatives of Federal Bureaus and irrigation-projects were present.

The second session was held at the California Institute of Technology at Pasadena, California, January 31, 1936, in affiliation with the Western meeting of the Section of Hydrology of the American Geophysical Union. The registered attendance at this session was 88. The attendance at the dinner and business session was 33.

The program, which follows, was based on a detailed questionnaire regarding snow-survey equipment and methods sent out by Chairman James E. Jones, Assistant Engineer, Department of Water and Power of the City of Los Angeles.

Program, Western Interstate Snow-Survey Conference
James E. Jones, Chairman

Coordination and standardization of snow-surveying. James C. Marr, Associate Irrigation-Engineer, Bureau of Agricultural Engineering, U. S. Department of Agriculture.

Extension of normals by precipitation-data and by comparison with another stream (questionnaire of January 4, 1935). Glenn L. Parker, District Engineer, U. S. Geological Survey, Tacoma, Washington, and Carl Elges, Agricultural Experiment Station, University of Nevada.

The effect of soil-absorption on snow-survey forecasting of stream-flow. H. P. Boardman, Chairman, Forecast Committee, Nevada Cooperative Snow-Surveys.

Calculation of normals for use with snow-survey data. Charles H. Lee, Consulting Engineer, San Francisco.

The effect of absorption on stream-flow forecasts. George D. Clyde, Irrigation-Engineer, Utah State Agricultural College.

The Adirondack Snow-Survey. Edwin S. Cullings, Secretary, Black River Regulating District, Watertown, New York.

Present progress in improving snow-survey equipment. J. E. Church, Meteorologist, Agricultural Experiment Station, University of Nevada.

Summary of replies to snow-survey questionnaire. James E. Jones, Chairman, Western Interstate Snow-Survey Conference.

Precipitation-surveys for anticipating water-supplies. H. K. Burton, Superintendent, City Water Department, and J. Cecil Alter, Meteorologist, U. S. Weather Bureau, Salt Lake City, Utah.

Regarding the questionnaire, the 75 replies received indicated a wide diversity or uncertainty of opinion with local experience furnishing its limited basis. This was inevitable in pioneer work. To bring the wider view of the Conference into more intimate contact with inexperienced surveyors in the enlarged field of the Federal-State System, the Executive Committee was expanded and the following members were elected:

Executive Committee 1936-37

Professor George D. Clyde, Director of Utah Cooperative Snow-Surveys, Utah Agricultural Experiment Station, Logan, Utah, Chairman

Harlowe M. Stafford, Snow-Supervisor, California Cooperative Snow-Surveys, Sacramento, California

James E. Jones, Assistant Engineer, Los Angeles Department of Water and Power, Los Angeles, California

Professor H. P. Boardman, Chairman of Forecast-Committee of Nevada Cooperative Snow-Surveys, University of Nevada, Reno, Nevada

R. A. Work, Associate Irrigation-Engineer, U. S. Division of Irrigation, Medford, Oregon
James C. Marr, Associate Irrigation-Engineer, U. S. Division of Irrigation, Boise, Idaho
R. L. Parshall, Senior Irrigation-Engineer, U. S. Division of Irrigation, Colorado Agricultural Experiment Station, Fort Collins, Colorado
W. A. Lamb, District Engineer, U. S. Geological Survey (Water-Resources Branch), Helena, Montana
Lynn Crandall, District Engineer, U. S. Geological Survey and Water Master District No. 36, Idaho Falls, Idaho
J. Cecil Alter, Meteorologist, U. S. Weather Bureau, Salt Lake City, Utah
Professor Joseph Kittredge, Jr., Department of Forestry, University of California, Berkeley, California

The Executive Committee was requested to assist the American Geophysical Union financially in the publication of Conference papers.

Publicity

The value of publicity was forcibly emphasized to the Chairman last summer by the universal interest in water, for the West had suffered both from drought and from floods. Conferences and inquiries have created an address-list far larger than that contemplated from the Questionnaire on Snow sent out when the Committee was originally formed. The Government departments naturally supply most of the list, and include particularly the Water-Planning Committee of the National Resources Committee, the Weather Bureau, Bureau of Agricultural Engineering, Forest and Park Services, Farm Loan, Range-Management, Soil-Conservation, and similar authorities. The exchange of views and publications has therefore grown formidable, but even more essential than before.

Owing to manifest errors in the compilation of Courses in Hydrology in American and Canadian colleges and schools, the report has been held back awaiting further verification.

Wide publicity service has been given snow-surveying by the Los Angeles Department of Water and Power by providing a movie of snow-surveying in the High Sierra. This movie was used first in southern California to bring the watersheds to the people and was then shown before the Western meeting of the American Meteorological Society at Los Angeles. It was later generously brought to the Nevada Student Chapter, American Society of Civil Engineers at Reno, Nevada, and the National Reclamation Association at Salt Lake City, Utah.

Ultimately it was loaned to the Northwest Scientific Association at Spokane, Washington, as a feature on its program in place of a lecture by the Chairman of the Committee on Snow abandoned because of the cost of travel. It is now under consideration by the United States Office of Experiment Stations in connection with the Department Exhibit at the Texas Centennial Exposition, if it can be made available, and has also been requested by the United States Geological Survey for display among Government departments at Washington and for the program of the International Commission of Snow at Edinburgh.

Apart from papers presented at the sessions of the Western Interstate Snow-Survey Conference, progress-reports have been made to the Association of Western State Engineers and the National Reclamation Association at Salt Lake City by James C. Marr, Associate Irrigation-Engineer, United States Division of Irrigation, respecting the Federal-State Snow-Survey System and a paper on snow-surveying was presented by Orrin Broberg, student at the University of Nevada, before the Southwest Student Convention of the American Society of Mechanical Engineers at Pasadena.

The following articles by the Nevada Agricultural Experiment Station have now been published and approximately 600 reprints have been distributed:

Principles of snow-surveying as applied to forecasting stream-flow, by J. E. Church, J. Agri. Res., v. 51, No. 2, 1935.
Snow-surveys as an aid to flood-forecast and control, by J. E. Church, Eng. News-Record, June 20, 1935.
The snow-survey and summer-precipitation, by J. E. Church, Geog. Rev., v. 25, No. 4, 1935.

The large monograph on "Snow-surveying with reference to forecasting stream-flow: Its problems and their present phases," whose size has long delayed its publication, is now being favorably considered by the United States Bureau of Agricultural Engineering. It may possibly form the first of a series of monographs published jointly by the Nevada Agricultural Experiment Station and the Bureau. The series as planned will be: (1) Principles of snow-surveying; (2) Snow-survey engineering handbook; (3) Possibilities of snow-surveying: A world view.

Radio publicity in snow-surveying has now been standardized in the West. The broadcasts of Western watersheds and snow-conditions initiated by the Nevada Agricultural Experiment Station in conjunction with the Farm and Home Hour of the United States Department of Agriculture have now been transferred to the United States Division of Irrigation which is developing the Federal-State Snow-Survey System. The following themes have been presented:

Snow-cover surveys and predicting water-supply. Prepared by W. W. McLaughlin, Chief, Division of Irrigation, United States Department of Agriculture, and delivered by Paul Ewing over KGO and nine other stations of the National Broadcasting Company, January 15, February 7, and February 20, 1936.

Status of snow-storage. A radio dialogue with Paul A. Ewing, over KGO and nine other stations of the National Broadcasting Company, February 27, and with A. T. Mitchelson, April 13, 1936.

Some practical applications of snow-surveying and stream-flow forecasting. Prepared and presented by George D. Clyde over Station KDYL and nine other stations of the National Broadcasting Company, March 11, 1936

District radio broadcasts will be extended to all districts and should ultimately include the East. The following have been reported for Nevada: (I) The water-supply outlook for this season; (II) International Snow-Survey Commission (given by Professor H. P. Boardman over KOH, Reno, Nevada, April 7, 1936).

Research

Research in snow and water is receiving steady support from the Water-Planning Committee of the National Resources Committee and is included by the United States Division of Irrigation as one of its essential interests. Such research has long been carried on by the Forest Service and the Agricultural Experiment Stations, for watersheds serve a triple purpose as conservers of water, timber, and forage, and weight must be given to each according to the local interest.

Thus the research-problems of the watersheds fall naturally into three divisions: Conservation, adjustment, and forecasting. Some problems are already under way but most are merely awaiting public attention or support. The outstanding problems are listed below with brief comment.

Conservation

(1) Snow-cover and subsequent forest fire-hazard. Suggested by United States Forest Service at Missoula, Montana. "Will the depth of the snow-cover determine the relative fire-hazard of the following summer?"

(2) The influence of forest-cover on the conservation of snow. (a) Under way by California Agricultural Experiment Station, leader--Professor Joseph Kittredge, Jr. (b) Completed by Intermountain Forest and Range Experiment Station, leader--C. A. Connaughton. "Fully-developed forests catch less winter snow than do completely denuded areas, but they regulate the melting of what they do catch, retaining it longer and releasing the water more gradually."

Adjustment

(1) The relationship between tree-growth and stream-runoff in the Truckee River Basin, California-Nevada. By Nevada Agricultural Experiment Station, leaders--George Hardman and Orvis E. Reil. Completed. "To insure the stability of farming enterprises in this area for a long period of time, it is necessary to provide for the maintenance of a reasonable balance between the area of land farmed and the available supply of irrigation-water. The curves of tree-growth, giving an essential long-time record of moisture-conditions, may assist in such planning."

(2) The value of tree-growth measurements in a study of precipitation-cycles. By Division of Forestry, University of California, leaders--W. E. Davis and A. W. Sampson (in progress).

Forecasting stream-flow

(1) Improvement of snow-sampling apparatus. By Nevada and Utah Agricultural Experiment Stations, leaders--J. E. Church and George D. Clyde (in progress).

(2) Elevation of maximum snowfall. Proposed by François E. Matthes, United States Geological Survey.

(3) Intensity of summer storms with elevation. By Nevada Agricultural Experiment Station and United States Forest Service, leaders--Carl Elges and Alexander McQueen (in initial stages).

(4) Effect of precipitation during runoff. By Nevada Agricultural Experiment Station, leader--J. E. Church (in initial stages).

(5) Water-table elevation as an index of departure in forecasted runoff. By Nevada Agricultural Experiment Station, leaders--George Hardman and Carl Elges (in progress).

(6) Determining a factor for priming of the soil.

(7) Effect of "Tight dams" in causing diversion-losses.

(8) The disturbing effect of alluvial soil and meadows on runoff.

(9) Desert-stream normals.

All four (6 to 9) under way by the Nevada Agricultural Experiment Station, leaders--J. E. Church, Carl Elges, and H. P. Boardman.

(10) Effect of Chinooks on the snow-cover.

(11) Effect of high winds in accelerating evaporation on larger bodies of water.

Both by a Cooperative Committee representing the United States Geological Survey (Water-Resources Branch), United States Weather Bureau, Montana Agricultural Experiment Station, Northern Rocky Mountain Station of United States Forest Service--all of Montana, and the Nevada Agricultural Experiment Station as Advisor; Chairman, W. A. Lamb, Helena (all plans made--waiting only for equipment).

[Similar projects have been proposed in Alberta and Colorado to widen the area and obtain greater diversity of conditions. The project in Alberta would be directed by Professor H. R. Webb, University of Alberta at Edmonton; the project in Colorado is being developed by R. L. Parshall, Colorado Agricultural Experiment Station and United States Division of Irrigation at Fort Collins.]

(12) Springless balance for weighing evaporation-pans in the field. By J. C. Stevens, Consulting Engineer, Portland, Oregon, and J. E. Church, Nevada Agricultural Experiment Station.

(13) Forecasting runoff of the Colorado River by precipitation-gages and snow-surveys combined. By United States Bureau of Reclamation, leader--E. B. Debler (under way).

(14) Improving methods of forecasting for low watersheds. By Nevada Agricultural Experiment Station and United States Bureau of Reclamation, leaders--J. E. Church and J. S. Moore, Superintendent, Yakima Project, Washington (proposed).

(15) Determining the minimum elevation of stable winter-snow with latitude. By United States Forest Service, leader--F. E. Thieme, Regional Engineer, Missoula, Montana (proposed).

Flood-forecasting and prevention

(1) Effect of withholding large volumes of water in storage-reservoirs at headwaters of streams on intensifying ice-gorge floods. Suggested by Robert E. Horton, Consulting Engineer, Voorheesville, New York.

(2) Relation of snow to floods, particularly as to the effect of snow-cover on synchronization of flood-waters from tributary streams. Leader--Gerard H. Matthes, Mississippi River Commission, Vicksburg, Mississippi.

(3) The value of late snows in protecting old snow against premature melting. By Nevada and Utah Agricultural Experiment Stations, leaders--J. E. Church and George D. Clyde (in progress).

[Still other problems are proposed in the questionnaire sent out by James E. Jones, Chairman, in preparation for the program of the Pasadena session of the Western Interstate Snow-Survey Conference (see Transactions of this session in present volume)].

Bibliography

A request based on the last Annual Report has come from Dr. W. Mörikofer, Superintendent of the Physikalisch Meteorologisches Observatorium, Davos, Switzerland, for bibliographical material on the physics of snow. Unfortunately progress in compiling a bibliography of snow and ice has been very slow. Federal Emergency Funds appeared to be available, but special Federal duties even more urgent doubtless claimed all spare time.

International Commission of Snow

The International Commission of Snow organized by the International Association of Scientific Hydrology at Lisbon in 1933 seems to have received universal approval and has already given impetus to measuring snow in places as remote as Argentina and China.

A generous ruling by President Smetana of the International Association has made it possible to invite all snow and ice countries to share in the Commission irrespective of membership in the International Association itself. The only restriction will be the denial of voting on official Association matters. Members have now accepted from Argentina, Australia, Austria, Canada, China, Czechoslovakia, Estonia, France, Germany, Great Britain, India, Italy, Latvia, Lithuania, Norway, Poland, Sweden, Switzerland, and United States of America.

Invitations have also been sent to Chile, Denmark, Finland, Japan, Spain, and the Union of Socialist Soviet Republics. All will doubtless accept. The Soviet Union is withholding acceptance until concerted Soviet action can be taken.

The Commission is fast outgrowing the limits of a commission in its size but not in its

VARIOUS PHASES OF INTEREST OF
COMMISSION OF SNOW AND ICE
AND THEIR RELATION
TO OTHER COMMISSIONS AND ORGANIZATIONS

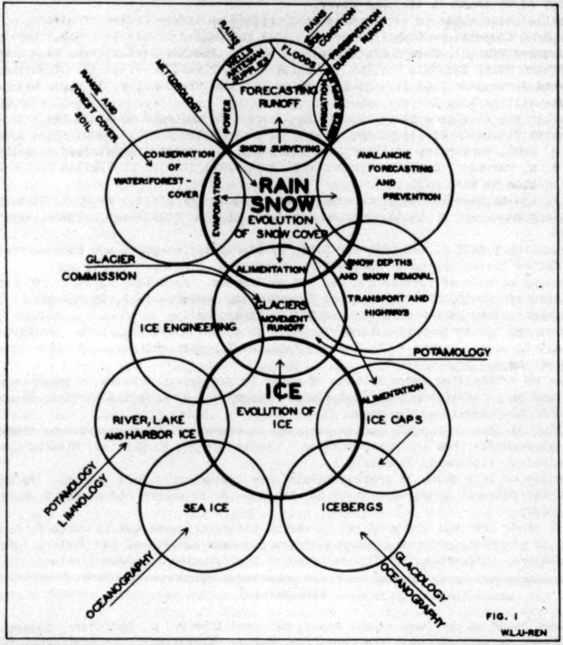
METEOROLOGY
RAINS
WELLS ARTESIAN SUPPLIES
RAINS
SOIL CONDITION
PRESERVATION DURING RUNOFF
FLOODS
IRRIGATION
POWER
FORECASTING RUNOFF
RANGE AND FOREST COVER
SOIL
SNOW SURVEYING
CONSERVATION OF WATER:FOREST-COVER
EVAPORATION
RAIN
SNOW
EVOLUTION OF SNOW COVER
AVALANCHE FORECASTING AND PREVENTION
GLACIER COMMISSION
ALIMENTATION
SNOW DEPTHS AND SNOW REMOVAL
TRANSPORT AND HIGHWAYS
GLACIERS MOVEMENT RUNOFF
ICE ENGINEERING
POTAMOLOGY
ICE
EVOLUTION OF ICE
ALIMENTATION
ICE CAPS
RIVER, LAKE AND HARBOR ICE
POTAMOLOGY LIMNOLOGY
SEA ICE
ICEBERGS
OCEANOGRAPHY
GLACIOLOGY OCEANOGRAPHY
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FIG. 1

compactness and response to a single chairman. However, State bodies also are being formed to advance local interests and concerted action. Every phase of the study of snow and ice and their applications is included. Consequently, some countries may have as many as fifteen members. The total membership of the Commission will exceed a hundred. To attain a guided progress, older scientists with ripened experience and younger men with energy and plans have been chosen.

President Smetana has also decided to make the Commission the uniting center of the other commissions and associations interested in hydrology and has approved of expanding the Commission of Snow into the Commission of Snow and Ice, except that the Commission of Glaciers shall retain its present project of measuring the movement of glaciers and may in the future withdraw from the Commission of Snow and Ice any other project in ice it may select. All other projects have generously been granted by the Commission of Glaciers, and glacialists particularly interested in the evolution of glaciers are joining the Commission of Snow.

The chart of Figure 1 has been drawn to show the broad central relationship of snow and ice.

The personnel list is nearing completion but should be withheld until all acceptances have been received. However, the United States members have now been chosen and their names and specialties can, therefore, be given.

Present personnel list from the United States

Prof. Dr. J. E. Church, Meteorologist, Nevada Agricultural Experiment Station, Reno, Nevada, President (Snow-surveying and stream-flow forecasting; conservation Greenland)
Prof. Dr. W. H. Hobbs, Emeritus, University of Michigan, Ann Arbor, Michigan (Glaciers, polar exploration)
Engineer R. E. Horton, Voorheesville, New York (Hydrology, evaporation, stream-flow, underground waters)
Prof. Dr. Joseph Kittredge, Jr., University of California, Berkeley, California (Conservation)
Prof. Dr. Laurence M. Gould, Carleton College, Northfield, Minnesota (Antarctic)
W. W. McLaughlin, Chief, United States Division of Irrigation, Berkeley, California (Water-supply forecasting)
Montrose W. Hayes, Chief, River and Flood Division, United States Weather Bureau, Washington, D. C. (Floods)
S. P. Fergusson, Research Associate, Blue Hill Meteorological Observatory, Milton, Massachusetts (Instruments)
Dr. Frederick W. Lee, Chief, Geophysical Division, United States Bureau of Mines, Washington, D. C. (Depth-meters)
Dr. W. J. Humphreys, United States Weather Bureau, Washington, D. C. (Snow- and ice-crystals)
W. A. Lamb, District Engineer, United States Geological Survey, Helena, Montana (International stream-flow forecasting)
Dr. Charles F. Brooks, Professor of Meteorology and Director, Blue Hill Observatory, Harvard University, Milton, Massachusetts (Precipitation)
Francois E. Matthes, United States Geological Survey, Washington, D. C. (High-level snow)
Prof. Dr. Arthur Casagrande, Harvard Graduate School of Engineering, Cambridge, Massachusetts (Highway surfaces and structures)
Dr. N. A. Bowers, Pacific Coast Editor, Engineering News-Record, San Francisco, California (Snow-removal)
Gerard H. Matthes, Mississippi River Commission, Vicksburg, Mississippi (Floods)
Lieut. Commander Edward H. Smith, United States Coast Guard, Washington, D. C. (Icebergs)
John C. Stevens, Consulting Engineer, Spalding Building, Portland, Oregon (Instruments)
Dr. O. E. Meinzer, Geologist in Charge, Division of Ground-Water, United States Geological Survey, Washington, D. C. (Ground-water)

The program for the coming triennial meeting is now reasonably complete but is still provisional. Owing to its size and the fact that only four hours can be granted to each of the eight commissions for formal programs, a special grant of three days preliminary to the formal opening of the International Association has been made to the Commission for its sole use. This is a growing custom and will permit the papers to be presented at length rather than by title.

The entire field has been covered to indicate the possibilities for research with the intention of narrowing future programs to reports on projects. The ultimate purpose is publication of the programs in the Bulletin for the distant and scattered membership.

The details so far as completed are set forth in the following program now awaiting final organic arrangement:

Provisional Program, International Commission of Snow
Meeting at Edinburgh, Scotland, Sept. 14-16, 1936

General

Organization and purposes of the International Commission of Snow: World view. President of Commission.
Need of a universal standard for measuring snowfall, precipitation, and snow-cover. Prof. Charles F. Brooks, Director, Blue Hill Meteorological Observatory, Harvard University, Milton, Massachusetts, U. S. A.
Snow-Surveying: Its principles and possibilities. Dr. J. E. Church, Meteorologist, Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada, U. S. A.
Ice-studies: Unification and publication. Prof. Dr. Antoni Boleslaw Dobrowolski, Directeur e.p. de l'Institut National Météorologique de Pologne, Warszawa, Pologne.

Snow-cover

La distribution de la neige en Italia et les chutes de neige dans les differents parties des Alpes et les Appennines. Prof. Filippo Eredia, Direttore dell'Ufficio Presagi, Roma, Italia.
(1) Snow as a form of precipitation and factors controlling distribution over the globe; (2) Drift-problems suggested by severe storms in the British Isles especially in relation to the permanent Scottish snow-beds. L. C. W. Bonacina, Royal Meteorological Society, London, England

Snow-cover--Continued

Gibt es im Gebirge eine Hohenzone maximalen Niederschlags? Prof. Dr. A. Wagner, Institut für Kosmische Physik, Innsbruck, Austria.

Studies of the snow-cover in Sweden. Swedish Committee.

The influence of the snow-cover on the earth-temperature. Swedish Committee.

Snow-maps of the year for Sweden. Swedish Committee.

Forecasting stream-flow

Stream-flow forecasting in Europe. Dr. Jan Smetana, Directeur des Instituts Hydrologique et Hydrotechnique. T. G. Masaryk, President of the International Association of Scientific Hydrology, Praha, Tchécoslovaquie.

Forecasting runoff with special regard to the influence of the accumulation of snow. Swedish Committee.

(1) Le role de la neige dans les crues de certains cours d'eau en Europe; (2) La prevision des debits d'été du Drac au moyen des precipitations nivales de la saison froide. Prof. Maurice Parde, Faculté des Lettres et Institut de Géographie Alpine, Université de Grenoble, Grenoble, France.

Snow-surveying in the High Sierra--A movie by George A. Lewis. Courtesy of Department of Water and Power of the City of Los Angeles, Los Angeles, California, U. S. A.

International forecasting and distribution of runoff by United States and Canada in St. Mary River Drainage-Basin (Montana, U. S. A., and Alberta, Canada). W. A. Lamb, District Engineer, United States Geological Survey, Helena, Montana, U. S. A. O. H. Hoover, Engineer in Charge, Dominion Water Power and Hydrometric Branch, Calgary, Alberta, Canada.

Forecasting runoff in Newfoundland by International Power and Paper Company of Newfoundland, Inc. Eric Hinton, Deer Lake, Newfoundland.

Snow-studies on Bogong High Plains by State Electricity Commission of Victoria, Australia. L. T. Guy, Assistant Engineer, Melbourne, Victoria, Australia.

Thermal and ice-régime of some rivers in U. S. S. R. and the conditions of foreseeing the same. F. J. Bydin, Bureau des Ingenieurs et Techniciens du Comptoir de Leningrad de Travaux de Constructions Hydroéléctriques du Svir, Leningrad, U. S. S. R.

Exhibit and discussion of apparatus for measuring snowfall and snow-cover, both accumulation and evaporation. President of Commission.

Runoff

Niederschlag und Abfluss im Hochgebirge der Schweizer Alpen. Dr. Otto Lütschg, Direktor, Institut für Gewässerkunde, Eidg. Technische Hochschule, Vice-President of International Association of Scientific Hydrology, Zürich, Suisse.

Avalanches

Schnee und Lawinenfilm. Prof. Dr. Wilhelm Paulcke, Emeritus, Riederau a. Ammersee, Germany.

The Swiss program of avalanche-investigation. M. Petitmermet, Directeur, Inspection fédérale des forêts, President, Commission fédérale des Neiges et des Avalanches, Berne, Suisse. Dr. Otto Lütschg, President Arbeitskommission, Zürich, Suisse.

Sculptural effects produced in the High Sierra by recurring avalanches. François E. Matthes, United States Geological Survey, Washington, D. C., U. S. A.

Streets and highways

Snow- and ice-removal. Dr. Howard T. Barnes, Professor Emeritus of Physics, McGill University, Montreal, Canada.

Symposium on snow-removal on mountain highways. Lacey V. Murrow, Director of Highways, State of Washington, Olympia, Washington. W. A. Smith, California State Highways, Sacramento, California. R. H. Baldock, Oregon State Highway Engineer, Salem, Oregon.

Frost in soils: Effect on highways and structures. Prof. Dr. Arthur Casagrande, Graduate School of Engineering, Harvard University, Cambridge, Massachusetts, U. S. A.

Ice in the soil. Swedish Committee.

Lake- and river-ice

Ice on small lakes. Swedish Committee.

Frazil and anchor ice in the rivers of Latvia. Peter Stakle, Vice-Director of the Latvian Marine Department, Riga, Latvia.

River-ice: Its dependence on meteorological factors. Swedish Committee.

The establishment of a working hypothesis of ice-phenomena in lakes and rivers. Prof. Dr. Eng. V. E. Timonoff, Member of the Research Institute of Hydrotechnics, Leningrad, U. S. S. R.

Frostwirkung auf die Abflussverteilung eines Flussgebietes. August Velner, Ingenieur, Leiter des Hydrometrischen Bureaus, Tallinn, Estonia.

Snow- and ice-physics

(1) The rôle of regelation in changing the properties of snow-water; (2) Mechanical properties of snow and ice; (3) Attempt of a program of theoretical and experimental investigations of properties of snow and ice. Prof. B. P. Weinberg, Leningrad, U. S. S. R.

The phenomena in the contact-zone between snow and soil during the melting of snow. Robert E. Horton, Consulting Hydraulic Engineer, Voorheesville, New York, U. S. A.

Snow- and ice-physics--Continued

Exceptional examples of compacted snow. Prof. Dr. W. H. Hobbs, Emeritus, University of Michigan, Ann Arbor, Michigan, U. S. A.

Kriechschnee und Schneekohäsion. Dr. h. c. Max Oechslin, Kantonsoberförster, Altdorf-Uri, Schweiz.

Glaciers

Die Firn und Schneegrenze. Dr. h. c. Max Oechslin, Kantonsoberförster, Altdorf-Uri, Schweiz.

(1) Arctic and Antarctic snow and ice.

Variations of glaciers and measurements of ablation. Prof. Dr. Hans W:son Ahlmann, Director Geographiska Institutet, Stockholms Högskola, Stockholm, Suede.

The growth and dissipation of the Ross Shelf ice. Dr. Laurence M. Gould, Professor of Geology and Geography, Carleton College, Northfield, Minnesota, U. S. A.

Die Temperatur am Boden des Grönländischen Inlandeises. Prof. Dr. Kurt Wegener, Direktor, Physikalisches Institut der Universität, Graz/Steiemark, Austria.

The difference in crystal-structure of summer and winter snow on the inland-ice of Greenland. Dr. Ernst Sorge, Berlin, Germany.

Outlines of future work on snow and firn on the Greenland Ice-Cap. Dr. Fritz Loewe, Scott Polar Research Institute, Cambridge, England.

A new depth (electrical-resistance) meter for ice and snow. Dr. Frederick W. Lee, Chief of Geophysical Division, United States Bureau of Mines, Washington, D. C., U. S. A.

Icebergs

Protection from icebergs. Prof. Dr. Albert Defant, University, Berlin, Germany. (By title) Lieut. Commander Edward H. Smith, United States Coast Guard, Washington, D. C., U. S. A.

Agenda for 1939 (Problems suggested, with cooperators)

(1) High mountain-snow.

The water-contribution of rime on mountain-tops. Salvatore Pagliuca, Blue Hill Meteorological Observatory, Milton, Massachusetts, U. S. A.

Excess of evaporation at high altitudes as shown by sunpits or nieve penitente. François E. Matthes, United States Geological Survey, Washington, D. C., U. S. A. Luciano R. Catalano, Buenos Aires, Argentina.

Height of maximum snow. François E. Matthes, United States Geological Survey, Washington, D. C., U. S. A. Prof. Dr. A. Wagner, Institut für Kosmische Physik, Innsbruck, Austria.

(2) Glaciers.

Luftverhältnisse bei den Lawinenniedergängen. Dr. h. c. Max Oechslin, Kantonsoberförster, Altdorf-Uri, Schweiz.

(3) World snow-maps: (a) Total precipitation; (b) total snow; (c) proportion of snow in total precipitation. Director Charles F. Brooks [in (c) by proxy], Blue Hill Meteorological Observatory, Milton, Massachusetts, U. S. A. Prof. Filippo Eredia, Direttore dell'Ufficio Presagi, Roma, Italia. Swedish Committee.

(4) The importance of seasonal snow for river-supplies of the spring and early summer in the Punjab. Dr. E. MacKenzie Taylor, Director, Irrigation Research Institute, Punjab, Lahore, India.

(5) Floods.

Relation of snow and ice to floods. Gerard H. Matthes, Chairman, Mississippi River Commission, Vicksburg, Mississippi, U. S. A. Dr. Ragnar Melin, Förste Statshydrografen, Statens Meteorologisk-Hydrografiska Anstalt, Stockholm, Sweden.

(6) Polar ice-caps.

The amount of snow-drift and sublimation of rime on the snow-cover of Greenland, as factors in its mass-bilanz. Dr. Fritz Loewe, Scott Polar Research Institute, Cambridge, England.

[A. R. Glen, Leader of the Oxford University Arctic Expedition to Northeast Land has been invited to give a short address on the scientific work of that Expedition.]

International Congress of Cryology

At its meeting at Riga, July 17, 1934, the Permanent Committee of the Hydraulic Conference of the Baltic States decided not to organize an International Congress of Cryology but rather to seek admission to the International Commission of Snow.* The Soviet Union thereupon undertook the summoning of such a Congress but has announced that the initial meeting must be postponed until 1937.

Owing to the broad and international character of the Commission of Snow, urgent invitations have been sent to Doctor Dobrowolski, founder of the Congress, and to the Soviet representatives to join the two organizations--at least in program--because of the difficulty to American delegates of attending both at widely different times. It is believed that the union will ultimately be effected.

Current publications

General

Montrose W. Hayes, Weather and water in 1935, Eng. News-Rec., v. 116, p. 223, 1936.

Lake Tahoe level controversy settled, Eng. News-Rec., v. 114, p. 408, 1935.

Robert G. Stone, Die Entwicklung der Amerikanischen Bergobservatorien und das derzeitige Netz von Bergstationen in den Vereinigten Staaten von Amerika, Sonderabdruck aus dem XLIII, Jahresbericht des Sonnblick-Vereines, 1934.

Bradford Washburn, The conquest of Mount Crillon, Nat. Geog. Mag., v. 67, pp. 361-400.

Snow

(1) General--

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Appreciation

The Chairman desires to mention again the generosity of the Nevada Agricultural Experiment Station which was not only the parent of Western snow-surveying but has acted as patron both of the American Committee on Snow and the International Commission of Snow. Without its cooperation and financial support, many of the activities of the Committee would have been impossible.

To the Experiment Station should now be added the United States Division of Irrigation, which not only shared in the expense of the trip to study Western watersheds last summer but is encouraging in every way possible the trip to Edinburgh and the watersheds of western Europe.

The Chairman also desires personally to pay tribute to the memory of Professor L. G. Carpenter, Colorado State College, remote but inspiring colleague in the study of effect of weather on the melting and runoff of snow, who died within the year. He was one of the aging generation of snow-pioneers.

Recommendation

To keep pace with the increasing interest in hydrology of the Western states, it is suggested that the Pacific Coast Meeting of the Section of Hydrology be quadrupled to serve the four divisions including roughly (1) California-Nevada, (2) Utah-Arizona-Wyoming-Colorado, (3) Montana-Idaho-Eastern Washington, and (4) Western Washington-Oregon. The Western Interstate Snow-Survey Conference could affiliate in each as before. Association could be had with the Western Division of the American Association for the Advancement of Science and the Northwest Scientific Association when these meet in the various districts.

Nevada Agricultural Experiment Station,
Reno, Nevada

REPORT OF COMMITTEE ON GLACIERS, 1935-36

François E. Matthes, Chairman

The membership of the Committee remains the same as stated in the Transactions of the 15th Annual Meeting, except that Kenneth N. Phillips has taken the place of Carl P. Richards, as representative of the Mazamas, of Portland, Oregon.

The Committee submits the following report on the variations of glaciers in the continental United States and Alaska for 1935 or, more precisely, for the 12-month period from the autumn of 1934 to the autumn of 1935.

Glaciers of Mount Baker

From H. V. Strandberg, Vice-President of The Mountaineers, Seattle, Washington, was received the first annual report on glacier-measurements on Mount Baker.

Easton Glacier in September 1935, the report shows, had receded 190 feet since the establishment of the base-line in 1934. From a photograph taken by Henry Engberg, in 1910, it is estimated that the Easton Glacier then was about 4000 feet longer than it is at present. It therefore appears to have been receding at an average rate of 160 feet per year. Although this figure is necessarily approximate, it is closely checked by the topographic map of Mount Baker, made by the United States Geological Survey in 1908. The position of the terminus indicated by that map is 4750 feet in advance of the present position, and the average recession for 27 years, accordingly, appears to have been 168 feet. The map shows the terminus at an elevation of 4200 feet, whereas the present elevation (determined by aneroid) is 5250 feet.

Glaciers of Mount Rainier

C. Frank Brockman, Park Naturalist of Mount Rainier National Park, reports that as the result of nearly normal snowfall during the winter of 1934-35, and of approximately normal summer weather in 1935, glacier-recession on Mount Rainier was considerably less rapid in 1935 than in 1934.

Nisqually Glacier receded only 54 feet, as compared with 155 feet in 1934. The average annual recession for the three years prior to 1934 was about 48 feet.

Paradise Glacier receded 23.5 feet at Point B and 74 feet at Point C. No measurement could be made at Point A, as it was covered with snow.

Stevens Glacier could not be measured, owing to destruction of the reference-point established in 1934.

Emmons Glacier receded 67 feet at the ice-cave from which the White River emerges, and 30 feet at the ice-wall to the north of the cave. The average recession for its terminus is therefore 48.5 feet, as compared with 132 feet in 1934.

Carbon Glacier receded 24 feet, as compared with 29 feet in 1934.

South Tahoma Glacier receded 61 feet, as compared with 73 feet in 1934 and 13 feet in 1933. (The recession of 1934 was omitted, by an oversight, from last year's report of the Committee.)

Glaciers of Mount Hood

From Kenneth N. Phillips, Chairman of the Research Committee of the Mazamas, of Portland, Oregon, a very complete report was received, including meteorological data, results of preliminary cryocinemeter-measurements, airplane photographs taken in 1935, and photographs taken in 1901 by Harry Fielding Reid, now extremely valuable for comparative studies.

Most of the material embodied in this report, together with data for previous years, is included in a paper by Mr. Phillips on "Recent changes in Hood's glaciers," published in Mazama, in 1935. Here only a few of the most essential facts can be presented.

Eliot Glacier on September 15, 1935, had receded 10 feet from its position in 1934. On October 19 its recession had increased to 12 feet. From photographs taken by Harry Fielding Reid on July 23, 1901, it is evident that the terminus then was situated 240 feet below the present base-line of the Mazamas, or 360 feet below its present position. (Probable error in location of terminus in 1901 is plus or minus 5 to 10 feet.)

Coe Glacier appears to have advanced 15 feet from its position in 1934, but there is some doubt as to the reality of this advance as the terminus in 1934 was deeply cloaked with moraine and ill defined.

Ladd Glacier could not be measured with accuracy because it was covered with snow at its lower end.

White River Glacier--No systematic measurements have been made of White River Glacier, but an estimate based on a photograph taken by Harry Fielding Reid in 1901 would seem to indicate a total recession of the terminus of about 1000 feet in 34 years.

Newton Clark Glacier--Comparison of photographs of Newton Clark Glacier taken in 1935 with Reid's photographs of 1901 shows a thinning of the terminal ice-cliff and a recession estimated at about 300 feet.

The excellent aerial photographs taken in 1935 show all the glaciers of Mount Hood in a condition of extreme depletion as compared with their aspect in 1901.

Glaciers of Mount Shasta

Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, reports that early in September 1935 the Konwakiton and Wintun glaciers still were mantled with last winter's snow at their termini, so that their changes in length could not be measured accurately. Both glaciers appeared to have held their own and perhaps even to have advanced slightly.

A base-line was laid out at the front of the Hotlum Glacier.

Mud Creek Glacier had receded 20 feet since 1934, but this recession was due, as in the preceding years, to the undercutting of its terminus by the caving off of the wall of volcanic ash at the head of Mud Creek Gorge, and not to climatic influences.

An unexpected revelation of the existence of old glacier-ice under the volcanic ash for a distance estimated at more than a mile down Mud Creek Gorge came as the result of a cloud-burst on the peak on August 28. The rain-water gullied the ash deeply, exposing the old black ice, which probably has lain buried since 1924, when Konwakiton and Mud Creek glaciers were confluent and formed an ice tongue 1 to 1-1/2 miles in length.

Similar exposures of old black ice were made by the gullying storm-waters in the canyons below the tongues of Wintun and Hotlum glaciers.

Mr. Kehrlein's report further contains several excellent aerial photographs taken by Army fliers in 1920 and again in 1935. Direct comparison of these two sets of aerial photographs reveals most impressively the extent to which the glaciers on Mount Shasta have receded and wasted away during the last 15 years. A detailed statement of even the more important changes that have taken place in these ice-bodies can not be given here for want of space.

Glaciers of the Sierra Nevada

From the beautifully illustrated report of Park Naturalist C. A. Harwell the following data are taken on the glaciers in and adjacent to Yosemite National Park:

East Lyell Glacier has advanced one foot since 1934. Measurements along an accurately surveyed line across the surface of the Glacier, on the other hand, show a reduction of 9.6 feet in the last two years.

West Lyell Glacier showed an advance of 7 feet, as compared with a recession of 14 feet in 1934.

Maclure Glacier showed no change. The central portion of the terminal moraine has caved in, due to the undermining action of a streamlet, and reveals clearly that most of the morainal material at the front of the Glacier rests on old ice.

Dana Glacier--The principal lobe, opposite station 4, shows an advance of 19 feet, as compared with a recession of 46 feet in 1934.

Conness Glacier advanced 12 feet at its east lobe, as compared with an estimated recession of 25 feet in 1934.

Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, contributes several photographs that record a marked glacial advance that occurred in the Sierra Nevada during the second decade of this century--an advance that has not thus far been recognized.

Photographs by Charles H. Lee show that in 1916 the Dana Glacier reached almost to the crest of its massive terminal moraine and had far greater thickness and volume than in 1885, when Prof. I. C. Russell photographed it, and several times its present thickness and volume. Photographs taken by the same observer in 1911 show that the North Palisade Glacier in that year was nearly level with its encircling moraine-wall, which now stands 20 to 40 feet above its surface. Photographs taken by Hans Leschke in 1935 indicate further lowering of the surface since 1934. A photograph of the Darwin Glacier taken by Leschke in 1934 indicates further recession and lowering of the surface of that ice-body since 1933.

Glaciers of Glacier National Park, Montana

Park Naturalist Geo. C. Ruhle reports following changes in the principal glaciers of Glacier National Park:

Blackfoot Glacier in 1935 showed an advance of 8 feet as compared with a recession of 10 feet in 1934.

Sperry Glacier--The central lobe has advanced 7.5 feet beyond its position in 1933. (No measurement could be made in 1934.)

Grinnell Glacier has receded 43 feet, as compared with 54 feet in 1934.

Agassiz Glacier has receded 79 feet since 1934. Its total recession since 1932, when the first reference-mark was set, is 154 feet.

Glaciers of Alaska

The data here presented are taken from a report by Wm. Osgood Field, Jr., who with Prof. Wm. S. Cooper, of the University of Minnesota, in 1935 made a joint expedition to Holkham Bay, Glacier Bay, the lower Copper River Valley, and Prince William Sound.

All these localities had been previously visited by either one or the other of the two observers, or by both. Field had visited Glacier Bay in 1926, the lower Copper River Valley in 1927 and 1931, and the northern inlets of Prince William Sound in 1931. Cooper had made botanical studies in Glacier Bay in 1916, 1921, and 1929, and in Holkham Bay in 1929. The only district visited in 1935 that was unknown to either member of the party was the western part of Prince William Sound, in which are situated Passage Canal, Blackstone Bay, Port Nellie Juan, and Icy Bay.

The purpose of the Expedition was a dual one, namely, to record changes in the extent and volume of the glaciers, and to study changes in the extent and character of the vegetation that have taken place, or are in progress, in the areas immediately adjoining the glaciers. Observations were made, further, on remnants of ancient forests that grew during prolonged periods of glacier-recession in areas that have been repeatedly covered by vast expanses of ice during post-Pleistocene time. Maps and charts, finally, were made of several bays and inlets for which topographic and submarine data were still lacking.

For the sake of brevity only the most essential data concerning the variations of the glaciers are here presented. A more comprehensive report, including all the other material, glacial and ecological, brought back by the Expedition, will be published elsewhere.

For many of the glaciers listed only estimates of advance or recession can be given for it is, in the nature of things, not possible to obtain precise measurements of the oscillations of irregular ice-fronts of great breadth. The estimates are, however, based on careful comparisons of photographs or charts of different dates and in any event indicate the true nature of the changes and the order of their magnitude.

Holkham Bay

Previous observations and photographs referred to: John Muir, Travels in Alaska, Houghton Mifflin Company, 1915; Wm. S. Cooper, photographs taken in 1929; United States Forest Service, photographs taken in 1932 and 1934.

North Dawes Glacier in 1880 was a tide-water glacier, visible from the main fiord, according to Muir's descriptions. In 1929 it had ceased to be tidal and had receded around a bend in the fiord. In 1935 the terminus had receded about 1000 feet from the position in 1929. Masses of ice still clung to the mountain-side above the surface of the Glacier, indicating recent shrinkage in volume. Recession and shrinking appear to be still in progress.

South Dawes Glacier has suffered but little change in length since 1929. The ice-front in 1935 probably stood close to its position in 1880.

Brown Glacier in 1880 was described by Muir as "a glacier of the first order sending off bergs." By 1929 it had ceased to be tidal and had retreated fully 2 miles up the valley. It has since continued to retreat and shrink at a rapid rate.

North and South Sawyer glaciers appear to have changed but little in length since 1929. Vegetation near the ice-fronts suggests that they are now as advanced as they have been for several decades. Photographs by the Forest Service indicate an advance of the South Sawyer Glacier between 1932 and 1934. The ice-fronts in 1935 were probably slightly more advanced than in 1934.

Glacier Bay

Previous observations and photographs referred to: J. B. Mertie, Jr., photographs taken in 1919; Wm. O. Field, Jr., observations and photographs made in 1926; Wm. S. Cooper, The recent ecological history of Glacier Bay, Alaska, Ecology, v. 4, 1923, and v. 12, 1931; United States Navy, aerial photographs taken in 1929; H. F. Reid and C. W. Wright, photographs taken in 1931.

Wood Glacier is now merely an ice-remnant occupying a low saddle. Shrinking and recession of margins has continued steadily ever since its alimentation was cut off. In 1931 the western end of the Glacier impounded a large lake, but now the central portion has collapsed and a northward draining channel has been opened under the ice, lowering the water-level considerably.

Geikie Glacier did not undergo any pronounced changes between 1929 and 1931, but since then its front has receded about 200 feet, its surface has been lowered considerably, and its margins have contracted correspondingly.

Small unnamed hanging glacier between Geikie and Wood glaciers has receded several hundred feet up the mountain-side since 1919.

Charpentier Glacier receded about 1500 feet between 1926 and 1931, and since then has receded about 1000 feet more. The small snow-fields at its head no longer aliment it sufficiently to maintain its volume.

Unnamed valley glacier northwest of Charpentier Glacier receded about 500 feet between 1926 and 1931, and since then has receded about 100 feet more. Its lower portion has decreased appreciably in volume.

Hugh Miller Glacier between 1926 and 1931 receded considerably on the south side of its medial moraine, but since 1931 its recession there has been slight. The central and northern portions of the terminus have receded rapidly since 1926.

Reid Glacier suffered little change between 1929 and 1931, but since then has receded fully 500 feet. Its surface has melted down considerably, so that a rock-outcrop over a mile back from the front, barely noticeable in 1929, is now prominently exposed. The two terminal moraines formed between 1899 and 1919 are now great bars extending from both sides of the inlet, nearly half a mile out from the ice-front.

Lamplugh Glacier between 1926 and 1929 receded about 300 feet at the western end of its front. Since 1929 this part of the Glacier has advanced beyond its position in 1926. The eastern end of the front has made similar oscillations, but its changes are more difficult to measure owing to the progressive development of an embayment in the border. A large subglacial stream now issues into this embayment and is building a bar on which the eastern portion of the ice-front rests.

Johns Hopkins Glacier, as is apparent from a comparison of distant photographs, was somewhat more advanced in 1926 than in 1929. Since 1929 its position has remained practically unchanged. In 1931 a small tributary glacier joined the main ice-stream on the south side, within a mile of the front, but this tributary has since shrunk and become detached.

Unnamed hanging glaciers--Only four of the numerous hanging glaciers in Johns Hopkins Inlet have been sufficiently photographed to permit determination of their recent behavior.

(1) The second ice-tongue southwest of the elbow-bend, on the southeast side of the Inlet, has receded and shrunk appreciably since 1929. Large detached masses of ice around the terminus in 1935 attested rapid shrinking still in progress.

(2) The third ice-tongue southwest of the elbow, conspicuous because of its forked terminus, appears to change but little. It was somewhat longer and thicker in 1931 than either before or since.

(3) The second largest glacier of the Inlet, situated on its southeast side, within 2 miles of the Johns Hopkins Glacier, has an active tidal front which photographs show in essentially the same position in 1926, 1931, and 1935.

(4) The first conspicuous ice-tongue on the northwest side of the Inlet, southwest of the big valley on the outer side of the elbow, was fully 500 feet above tide-water in 1929. In 1935 it had reached tide-water but did not have an actively discharging front. Its terminus is now shrinking and may be expected to recede soon.

Margerie Glacier, according to observations made in 1926, 1929, 1931, and 1935, has remained essentially unchanged in length throughout that period.

Grand Pacific Glacier advanced slightly between 1926 and 1929, and advanced from 1000 to 2000 feet between 1929 and 1931. In this great advance its front in all probability crossed the International Boundary into United States territory. Between 1931 and 1935 the Glacier receded several hundred feet, but its front remained far in advance of the positions in 1926 and 1929 and probably close to the Boundary. In 1935 fully three-eighths of the eastern part of the ice-front rested on a bar, and the remainder appeared to be in shallow water.

Rendu Glacier advanced several hundred feet between 1926 and 1931, and a similar distance between 1931 and 1935. A small tidal ice-cliff existed in the middle of the front in 1926 and 1929, but this had disappeared by 1931. A well-developed push-moraine in front of the terminus showed that the advance was still in progress in 1935.

Carroll Glacier in 1919 was still an actively discharging tidal glacier. By 1926 it had receded far enough to be non-tidal. Rapid recession and shrinking have continued up to 1935. This Glacier, like several others that drain into Muir Inlet, is a dwindling remnant of a once large, connected glacier-system.

Morse Glacier is probably receding, but no precise measurement of the rate could be obtained.

Plateau Glacier and its alimenting snow-field, the Cushing Plateau, appear to be shrinking, and its terminus in Muir Inlet is receding. The ice-front, however, continues to discharge bergs. The ice-tongue which drains into upper Muir Inlet also has receded and shrunk in volume since 1926.

The Cushing Plateau is a remnant of the formerly vast Muir Glacier System. Cut off, as it now is, from all other sources of supply, it lies at too low a level to receive sufficient snow by precipitation to maintain its volume and consequently is gradually wasting away.

Muir Glacier--Continued bad weather in 1935 precluded accurate determination by triangulation of the position of the ice-front, as had been planned, and its recession therefore can only be estimated from photographs. Recession was very rapid from 1919 to 1926, amounting to 1-1/2 miles. Between 1926 and 1935 the glacier receded about 1/2 mile more. Its ice-front remains today the most active one in the Glacier Bay District and discharges by far the largest bergs. It still terminates in very deep water.

Still connected with the Muir Glacier, but wasting rapidly, are vast ice-fields whose alimentation has been cut off by the shrinking of the main glacier. Three active ice-streams issuing from extensive snow-fields situated well above the summer snow-line continue to aliment the Muir Glacier.

Casement Glacier, whose ice-front in 1907 was continuous with that of the Muir Glacier and discharged ice-bergs, by 1919 had become a separate, non-tidal mass, still fronting on the beach. By 1935 it had receded still farther and its entire lower section had been resolved into an irregular pattern.

Adams Glacier since its separation from the Muir Glacier in the early years of this century has shrunk with great rapidity, its former source of supply having been cut off. It is now a nearly stagnant mass. Large portions of it have been undermined by tide-water and have melted away. Several tributary glaciers have become separated from it and others have almost disappeared. The whole Glacier is likely to disappear in the next decade or two.

Summary--During the last ten years, nine of the seventeen large or moderately large glaciers of Glacier Bay have been receding steadily, and three others have reached the vanishing stage. One glacier made a recent advance, but in 1935 was again receding. One was receding until 1929 but since then has been advancing. One has been steadily advancing, and two have remained unchanged. Among the five small hanging glaciers mentioned, two show no appreciable change, two have been receding, and one has advanced considerably but in 1935 was again receding. The general recession of the glaciers of Glacier Bay, which has been going on for more than a century, is therefore still in progress, though at a lessened rate, and with several notable exceptions.

Lower Copper River Valley

Previous observations referred to: Wm. O. Field, Jr., observations and photographs made in 1927 and 1931.

The glaciers here mentioned were observed only in passing, mostly from a considerable distance. The Scott, Sheridan, and Childs glaciers appear to have shrunk slightly in volume. One tongue of the Grinnell Glacier is more advanced than in 1931, but stagnant ice on its eastern margin shows that recession is taking place following a slight recent expansion. Miles Glacier shows evidence of shrinking, and the surface of its lower portion has been lowered considerably, but the terminus has changed but little in position. Allen Glacier also has shrunk in volume, and the terminal portion of its active ice-body has become increasingly detached from the large old piedmont lobe. This vast area of old ice, heavily mantled with morainic material, on which alder-thickets grow, is melting down very slowly.

Prince William Sound

(A) Glaciers of the Northern Inlets, from Port Valdez to Harriman Fiord--Previous observations and photographs referred to: Wm. O. Field, Jr., observations and photographs made in 1931, summarized in "The glaciers of the northern part of Prince William Sound, Alaska," Geog. Rev., July 1932; "The mountains and glaciers of Prince William Sound, Alaska," American Alpine Journal, 1932.

Valdez Glacier has continued to recede steadily, as in 1931. The average recession of its broad terminus since 1931 is about 200 feet.

Shoup Glacier has suffered no change in length since 1931, but has locally shrunk slightly in volume.

Columbia Glacier has advanced considerably since 1931 along the entire length of its vast front. At its western margin the measured advance is 342 feet. On Heather Island one measurement, representative for that section, shows an advance of 237 feet. The lobate eastern margin in places has advanced more than 400 feet. The entire terminal portion of the Glacier has become much thicker and more intensely crevassed.

Meares Glacier has remained stationary since 1931. The medial moraine between the ice-masses contributed by the north and south branches of the Glacier has moved northward, showing that the south branch has become relatively stronger in the last four years. A small hanging glacier, which in 1931 did not reach the south branch, has since advanced and is now a tributary.

Yale Glacier since 1931 has advanced about 200 feet into thickets of mature alders, both along the eastern part of its front and at its eastern margin. At its western margin the ice has advanced only 50 feet and is still 50 feet from the farthest limits it has reached during the last few decades. The second tributary back from the front on the east side has increased in volume since 1931.

Harvard Glacier has advanced slightly since 1931--about 150 feet at its western margin and 100 feet at its eastern margin. On its western margin the Glacier has spread laterally into mature alders and is now probably farther forward than it has been for several centuries.

Baltimore Glacier--This small hanging glacier has advanced about 300 feet since 1931.

Smith Glacier has not changed appreciably in either length or volume since 1931 but now presents a markedly different appearance. In 1931 the lower portion was largely covered with moraine, and less than one-third of the ice-cliff was composed of moderately clean ice. In 1935 clean white ice reached all the way down to the ice-front and made up more than three-fourths of the cliff. The large southern lateral moraine was greatly constricted by the white ice and correspondingly higher and more concentrated.

Bryn Mawr Glacier since 1931 has advanced and spread laterally on both sides of its terminus. The rock-cliffs that were visible at its front in 1931 are now buried under the ice.

Vassar Glacier--In 1935 white ice extended farther down into the moraine-covered lower portion than in 1931, and a subsidiary tongue had advanced south of the main terminus. The moraine-covered terminus, however, had shrunk in volume and had a perceptibly lower surface.

Wellesly Glacier--The margins of the terminus in 1935 were slightly farther advanced than in 1931, but the central portion, which formerly jutted out in the form of a cape, had hardly changed in position. The barren zones at the sides were much reduced in size by lateral expansion of the terminus.

Coxe Glacier has remained unchanged in length since 1931, but the southern margin of its lower portion appears to have thickened and expanded somewhat laterally.

Barry Glacier--The westernmost ice-tongue of the terminus has advanced 150 to 200 feet since 1931, but the rest of the ice-front remains unchanged in position.

Cascade Glacier appears to have undergone no change since 1931.

Serpentine Glacier shows no change since 1931 except at the northern end of its terminus, where the ice-cliff has advanced about 50 feet, probably as a result of the shallowing of the water and the consequent added protection of the ice from its melting effect.

Baker Glacier--Since 1931 the lowest ice-tongue has advanced between 150 and 200 feet, and the eastern part of the terminus has thickened and advanced slightly. The fan-shaped mass of snow and ice at the base of the frontal cliff is higher and larger than in 1931.

Detached Glacier--The lower ice-tongue has advanced about 100 feet since 1931.

Surprise Glacier shows little change since 1931. Its northern margin has advanced somewhat, but its southern margin remains unchanged in position.

Cataract Glacier since 1931 had advanced from a position 50 to 100 feet above sea-level down to tide-water. The lower portion of the Glacier, for about 1000 feet up from the front, has thickened and spread laterally.

Roaring Glacier shows no change in length since 1931. The fan-shaped mass of snow and ice below the frontal cliff also remains unchanged, but several crevasses are visible in it.

Harriman Glacier between 1931 and 1935 advanced 100 to 150 feet at its western margin, but its eastern margin was subject to various oscillations. It first advanced 192 feet, then receded 17 feet plus an unknown distance, then readvanced this unknown distance, and finally receded 20 feet. The last small retreat was probably seasonal. Other movements may have occurred but, if so, the evidence is obliterated. As a net result, this portion of the ice-front in 1935 was 155 feet in advance of its 1931 position. The west-central portion of the ice-front in 1935 rested largely on a sand-bar. This bar has grown considerably since 1931.

Unnamed hanging glacier on west side of valley above lower part of Harriman Glacier has advanced slightly beyond its position in 1931 and is thicker in its terminal portion.

Dirty Glacier receded on an average about 200 feet between 1931 and 1935.

Wedge Glacier, to judge from distant photographs, has undergone no appreciable change since 1931.

Toboggan Glacier has receded since 1931--183 feet at its western margin and 72 feet at its eastern margin. The entire lower portion of the Glacier has shrunk in volume and its surface has been lowered considerably.

The Crescent, Amherst, Dartmouth, Williams, Barnard, Holyoke, Bettles, and Pigot glaciers, all in Port Wells, have barren zones in front of their termini and along their margins. No comparative observations are available but the evidence clearly points to recent shrinkage and recession.

(B) Glaciers of the Western Inlets, from Passage Canal to Icy Bay--Previous observations referred to: U. S. Grant and D. F. Higgins, "Coastal glaciers of Prince William Sound and Kenai Peninsula, Alaska," Bulletin 526, United States Geological Survey, 1913; Ralph S. Tarr and Lawrence Martin, "Alaskan glacier studies," National Geographic Society, 1913.

The Seth, Billings, Longfellow, and Whittier glaciers, in Passage Canal, all had frontal and lateral barren zones in 1935. Recent recession and shrinkage is assumed for all of them, and in the case of Longfellow Glacier can be estimated at fully 500 feet since 1910.

All the principal ice-tongues in Blackstone Bay, in 1935, appeared to be in about the same position as described by Martin in 1910.

Tebenkoff Glacier has receded fully 1000 feet since 1910. A rocky knoll has been uncovered on which is a remnant of an inter-glacial forest, the first to be found in the Prince William Sound Area.

Cotterell, Taylor, Claremont, and Applegate glaciers, in Port Nellie Juan, have receded and shrunk in volume since 1910, as is attested by frontal and lateral barren zones.

Kings Glacier has receded so far that its eastern tributary no longer joins it, and the two are now separate glaciers.

Falling Glacier appears to have receded less than the preceding and still has an ice-tongue that reaches tide-water. Conspicuous barren zones around its margins, however, indicate that it too has recently shrunk in volume.

Nellie Juan Glacier has receded along its entire front. At its western margin the recession since 1910 measures 1912 feet. At its eastern margin the ice-cliff has receded 1532 feet. The eastern land-terminus is now fronted by a barren zone 500 to 1000 feet in width which was occupied by the ice during the last 50 years. A forest of mature trees immediately beyond this zone shows that this advance was the greatest for several centuries. During the culminating stage of this advance the ice apparently obstructed the outlet of a lake nearby and raised its level about 50 feet.

Ultramarine Glacier has receded more than 1000 feet since 1908, and its recent history appears to have been similar to that of the Nellie Juan. Vegetation is creeping up slowly, but the frontal barren zone is still 800 to 900 feet wide.

Princeton Glacier has receded and shrunk greatly in volume.

Chenega Glacier has hardly changed in length since 1910, and its front continues to be one of the most actively discharging ice-cliffs in Icy Bay.

Tiger's Tail Glacier has probably shrunk somewhat in volume. In 1935 it still reached practically down to tide-water, but it is doubtful whether any icebergs were being discharged from its front.

Tiger Glacier in 1935 had advanced and covered the rocks which in 1910 were exposed beneath a large part of the ice-front. This advance, though probably small, is further attested by the fact that no barren zones remain along the margins, and the ice is close to growths of mature alders.

Summary for Prince William Sound--Of the ten large glaciers observed in the northern inlets, from Port Valdez to Harriman Fiord, only one has receded since 1931, three have remained unchanged, three have advanced along their entire fronts, and three have advanced along part of their fronts.

Of the fifteen smaller glaciers only two have receded, eight have advanced (some only slightly), and five have remained unchanged. Eight other glaciers for which accurate data are lacking appear to have receded.

It is significant that all the glaciers, large and small, which come from snow-fields or cirques at high elevations on the south side of the Chugach Range, are either advancing or stationary, while the glaciers that issue from cirques at lower levels and from snow-fields not on the main range are receding.

Of the twenty-five glaciers observed in the western inlets, from Passage Canal to Icy Bay, thirteen have receded since 1910, eleven appear unchanged (some of them may have receded slightly), and only one has definitely advanced. All these glaciers head in cirques and snow-fields at relatively low altitudes.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON EVAPORATION, 1935-36

S. T. Harding, Chairman

During the past year two members have been added to this Committee, Messrs. Blaney and Harding. The present list of members is as follows: Harry F. Blaney, 600 Federal Building, Los Angeles, California; N. W. Cummings, San Bernardino, California; R. E. Kennedy, Denver, Colorado; H. H. Kimball, Washington, D. C.; G. F. McEwen, La Jolla, California; Burt Richardson, La Jolla, California; Carl Rohwer, Fort Collins, Colorado; C. M. Saville, Hartford, Connecticut; Thorndike Saville, New York, New York; C. V. Theis, Washington, D. C.; S. T. Harding, Berkeley, California.

Two papers on evaporation were presented at the meeting of the Section of Hydrology at Pasadena, California, February 1, 1936. These were both entitled "Evaporation from water-surfaces: Status of present knowledge and need for further investigations," the authors being N. W. Cummings and A. A. Young.

A draft of a proposed Report for the Committee was prepared by the Chairman and sent to the members March 10, 1936, with a request for comments. Replies have been received from five of the ten members.

The limited number of replies received from the members of the Committee and the divergence of views expressed, makes it inadvisable to attempt to present any report as a Committee. The following expressions represent a statement by the Chairman of the Committee only, and should not be interpreted as committing any of the members of the Committee.

Activities in the field of evaporation from water-surfaces may be divided into two parts. One of these represents the observation of evaporation in order to determine its amount at different places and times and the other represents the investigational and research activities in the study of the factors affecting evaporation and the development of equipment and methods for its observation.

The recent Report of Standards and Specifications for Hydrology-Data of the National Resources Committee recommends the establishment of additional observational evaporation-stations using Weather Bureau equipment. Two points of view have been expressed on this matter by members of the Committee on Evaporation. Some members favored the establishment of such stations, others considered the uncertainties in the interpretation of results from United States Weather Bureau pans made it preferable to concentrate on research in the methods and equipment for the observation of evaporation before expanding the number of observational stations.

The inability to agree on the adequacy of present observational methods emphasizes the need for a research-program seeking to develop equipment for such observations and determining the relationship between the results obtained and evaporation from large water-surfaces.

There is a need for an evaporation-pan which will be a direct measure of the evaporation from large water-surfaces. This relationship should preferably be as near unity as practicable, but this is not necessary if it is constant. Coefficients for various forms of pans have been determined which give fairly dependable results when applied to the annual evaporation. As pointed out in the papers of Mr. Cummings and Mr. Young, the coefficients vary materially for shorter periods or under variable weather-conditions. The agreement of the coefficients for annual evaporation is explainable by the usual limited range in variation in annual temperature and other climatic factors. Within shorter periods where material variation occurs in the climatic factors the agreement is not so consistent.

There is need for a more extensive and thorough study of evaporation-equipment in an effort to develop methods of observation that will be proportional to evaporation at all times. This study should include all types of equipment that have been proposed, and, it is hoped, might develop some new types as a result of its work. It should be adequately financed and staffed so as to include training and experience in both the fundamentals of the processes governing evaporation and the needs of the field in which the results will be applied. It should be organized on a basis which will permit its maintenance long enough to secure conclusive results.

One essential in such a study is a means of securing the evaporation from a sufficiently large water-surface to serve as a basis for comparison with the results from different types of equipment. Opinions differ as to the size required for this purpose. The best basis is an actual large water-area from which evaporation can be directly measured. There are lakes in the West where inflow is infrequent and is measured and where seepage inflow and outflow are negligible in amount. Such a location is well adapted to the type of investigation suggested.

The Committee on Evaporation has had the usual difficulties that such committees encounter in trying to function by correspondence. It is questionable whether the results obtainable without meetings of the Committee justify the effort expended. There are questions in the field of evaporation on which a functioning committee should be able to be useful as a clearing house for different points of view and in supporting a program of investigational work for their clarification.

The Committee has adopted no definite program for the coming year. If the Section of Hydrology desires to continue a Committee on Evaporation, it is suggested that such a Committee might receive and consider discussions from any member of the Union on the papers presented by Messrs. Cummings and Young, and attempt to present the results in its report for next year. Opportunities for such discussions have not been generally available on papers presented in the Proceedings. From these results the Committee might be able to prepare and agree upon a report covering the extent and character of both observational and investigational work in this subject and to propose a program for its accomplishment.

12 Engineering Building,
Berkeley, California

REPORT OF THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, 1935-36

Charles H. Lee, Chairman

The membership of the Permanent Research Committee on Absorption and Transpiration remains as reported in the Transactions of the 15th Annual Meeting, with the exception of Dr. J. E. Weaver, who resigned June 25, 1935.

The Committee's report consists of a brief review of current work and published reports on the subject of absorption and transpiration in the United States, to the extent that it has been reported by members of the Committee. Discussion of the List of Terms with Definitions, accompanying the 1934-35 Report of the Committee (Appendix A), has been received during the year and accompanies the present report as Appendix A. The main report was not prepared sufficiently in advance for submission to members of the Committee, and represents the views of the Chairman only.

Research in absorption of rainfall and transpiration by the California Forest and Range Experiment Station, United States Forest Service, Berkeley, California

This work is being carried on intensively as outlined in previous reports. Several papers on special phases of the San Dimas Canyon work have been prepared for presentation at meetings of technical societies, but no comprehensive report on the main subjects of research has yet been made. During the current year selection has been made of seven 40-acre watershed-tracts in the Kings River Area, Fresno County, California, for intensive study of the same character as being carried on at San Dimas. These areas will each be controlled by dams and measuring devices at the lower ends. A total of from 60 to 70 rain-gages and two complete meteorological stations are being established. The vegetation consists of digger pine, woodland, and grass. The effect of both burning and intensive grazing will be observed.

Research in absorption of rainfall and stream-flow by the Appalachian Forest Experiment Station, United States Forest Service, Asheville, North Carolina

Research studies are being continued as described in previous reports. No results have as yet been published. In addition to the studies of absorption and runoff from watersheds with continuous streams, a number of small drainages ranging from one-half acre to two acres are under observation. Here catchment-basins with divisibility-devices are installed to obtain a record of the storm-flow. Also, small plots 8 by 8 feet are employed for special soil-profiles where the chief purpose is to study absorption both as surface storm-flow and as storm-seepage.

Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture

Research-work of this agency has continued as outlined in previous reports of the Committee. The work on transpiration and evaporation from natural vegetation along stream-channels and in tanks has been completed, and the results have been published in bulletins by the Division of Water-Resources, State of California, together with a report of similar work on Santa Ana River by the Water-Resources Branch, Geological Survey, United States Department of the Interior. Both investigations were carried on in cooperation with the Division of Water-Resources, State of California.

The report is entitled Bulletin No. 44, South Coastal Basin Investigation--Water-losses under natural conditions from wet areas in Southern California, 1933: Part I--Consumptive use of water by native plants growing in moist areas in Southern California, by Harry F. Blaney; Part II--Ground-water supply and natural losses in the Valley of Santa Ana River between Riverside Narrows and the Orange County Line, by Harold C. Troxell.

This report presents the most comprehensive research-work done to date on rates of transpiration from natural vegetation. Observations were carried on over a two-year period and included tank-measurements of use of water by salt-grass, Bermuda grass, tules, and cat-tails, willows, wire-rush, and use of water by mixed stream-border vegetation consisting principally of alder-trees in a mountain-canyon, and by mixed bottom-land vegetation consisting principally of willow and cottonwood trees and natural grasses and swamp-plants along a valley-stream. The determination of transpiration from stream-border vegetation was based upon accurate stream-flow measurements from which losses could be computed, and included continuous records of elevation of the adjacent water-table.

Other reports prepared by members of the Division of Irrigation in Southern California, which appeared during the year, are the following:

(1) "Water-penetration in hardpan citrus soils," by Colin A. Taylor, Associate Irrigation-Engineer, Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture (Agricultural Engineering, v. 15, No. 6, June 1934). This report discusses the problem of irrigating soils with a plow-sole. It points out the wide difference in the ability of different areas between tree-rows to absorb water.

(2) "Use of a limited water-supply for irrigating citrus orchards," by Colin A. Taylor, Associate Irrigation-Engineer, Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture. This was published in "Report on progress-conference on water-conservation, Los Angeles, California, March 13-14, 1935," by Committee on Conservation of Water, Irrigation Division, American Society of Civil Engineers, page 23.

(3) "The effect of decreasing soil-moisture supply on size of lemon fruits," by Colin A. Taylor, Bureau of Agricultural Engineering, and J. R. Furr, Bureau of Plant Industry, United States Department of Agriculture (paper presented before the American Society of Horticultural Science, St. Louis, Missouri, January 1, 1936).

(4) "Utilization of the waters of Mojave River, California," by Harry F. Blaney and Paul A. Ewing, Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture (August 1935). This is a 142-page mimeographed report, issued by the Department of Agriculture, and has a chapter on water-supply which discusses the absorption- and transpiration-losses along the Mojave River.

(5) "Some factors affecting the rate of percolation on water-spreading areas," by Dean C. Muckel, Junior Civil Engineer, Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture. This paper was presented at the Pacific Coast Meeting of the American Geophysical Union, January 31, 1936, and appears later in these Transactions.

The report on storage of water underground by spreading, covering all of Southern California, has just been completed and forwarded to Washington for publication.

Ground-Water Division, United States Geological Survey, Washington, D. C.

The results of rainfall-absorption observations at Lodi, California, are still under study and have not as yet been published.

The national program of water-level measurements in wells has been furthered by the publication in mimeograph form of the Report of the Committee on Observation-Wells, United States Geological Survey, under the title "A preliminary manual of methods, May 1935." All aspects of the technique of water-pressure level-measurements in wells are covered in detail. The relation of this work to that of this Committee can be seen by the following quotations:

"Areas of natural ground-water discharge--Some wells should be located in areas where evaporation and transpiration from the zone of saturation are active, as shown by the presence of typical swamp-loving plants. The wells in such areas should be located chiefly with references to differences in types and density of vegetation, in types of soil and subsoil, and in depth to the water-table. Wells near a spring or seepage-area may disclose significant facts about the relation of the water-level to the spring-discharge.

"Soil and vegetation--Differences in the amount of rain and snow-water that penetrates to the water-table and in the speed of penetration are largely determined by the types and density of the vegetation, the character of the soil and subsoil, and the tillage and cropping of the soil. To obtain information relating to ground-water recharge, observation-wells should be located with reference to differences in these controlling factors."

Water Conservation Committee, Irrigation Division, American Society of Civil Engineers, 925 Central Building, Los Angeles, California

The papers presented at the Los Angeles, California, meeting of this Committee in March 1935, have been published in bound mimeograph form by the American Society of Civil Engineers under date of December 1935. Useful papers are included on the subjects of soil-absorption and transpiration in citrus orchards, water-spreading, runoff from small experimental plots, erosion and runoff from brush-covered mountain and cultivated sloping areas. Resolutions were adopted by the Conference on safeguard of watersheds, check-dams in mountain areas of Southern California, spreading-grounds and flood-channels, economic use of water in irrigation, experimental runoff-plots, etc.

Special Advisory Committee to the Water-Resources Committee, National Resources Committee, Washington, D. C.

This Committee has prepared a detailed report on Standards and Specifications for Hydrologic Data dated November 1935, which contains much of interest on the subjects of absorption and transpiration. Chapter VII, entitled "Evaporation from moist soils and evapo-transpiration," discusses collection of data, compilation, publication, qualifications of personnel, and preparation of manual on methods of determining evapo-transpiration and evaporation from soil-surfaces with water-tables at various depths. Chapter IX, "Special projects," contains recommendations for work-relief projects as follows: (a) Project for the study of infiltration-capacity and soil-moisture; (b) project for the study of the consumptive use of water.

The report, although not entirely up to date in recommendation of equipment for collection of special data, is carefully prepared and should serve a very useful purpose in helping to standardize the collection of hydrologic data. It reflects the viewpoint of the user of data rather than that of the research-worker.

Miscellaneous

Publication during the year has been noted of the following papers: "Wetting and spreading properties of aqueous solutions," by H. L. Cupples, Bureau of Entomology and Plant Quarantine, United States Department of Agriculture (Industrial and Engineering Chem., v. 27, p. 1219, October 1935); "Soil-water movement as affected by confined air," by W. L. Powers, Soil Scientist, Oregon Agricultural Experiment Station (J. Agric. Res., v. 49, No. 12, December 15, 1934).

58 Sutter Street,
San Francisco, California

APPENDIX A--DISCUSSION ON LIST OF TERMS WITH DEFINITIONS

(1) Memorandum submitted to Charles H. Lee, Chairman, under date of November 26, 1935, by Mr. R. F. Walter, Chief Engineer, Bureau of Reclamation, United States Department of the Interior: In conjunction with your list of definitions given on pages 398-404 of Transactions of the American Geophysical Union, 16th Annual Meeting, 1935, the enclosed memorandum of May 16, 1935, may be of some interest. Our field of investigation (the structural suitability of earth-dam materials) is of course different from that in which the Committee is primarily concerned, but the application of the term "phreatic" to the boundary between zones of positive and negative hydrostatic pressures might have some virtue in its work as well.

Ground-water classifications (phreatic and capillary zones)

(Memorandum to E. W. Lane, Research Engineer, by D. P. Barnes, Assistant Engineer, Denver, Colorado)

(a) Recent experiments on the flow of ground-water both in the Earth Laboratory of the Bureau of Reclamation and elsewhere have demonstrated that where a zone of complete capillary-saturation exists in conjunction with a flowing ground-water table, flow will take place between the zones; the line of zero-pressure thus ceases to represent either a stream-line or a saturation-line, both of which identities are generally conceded when capillary-effects are ignored. In order to prevent increasing confusion of terms, the following definitions and distinctions are proposed.

(b) Capillary-zone versus gravity-zone--No significant difference appears to exist between the character of the flow in a completely saturated capillary-zone and that of the flow in the zone of positive pressure. The direction of flow is determined in either zone by the boundaries of the permeable material and by the available capillary-rise. The only distinction remaining between the zones is that of their hydrostatic pressures which pass from positive in the gravity-zone to negative in the capillary-zone; in other words, the line of zero-pressure thus becomes the boundary which marks the transition from capillary-water to gravity-water or the reverse.

(c) Terminology--In 1923 O. E. Meinzer (U.S. Geol. Surv. Water-Supply Paper No. 489, pp. 38

et. seq.) presented a brief etymological sketch of the term "phreatic," stating that it was first "introduced by Daubree (a) to designate the water in the zone of saturation except the deeper water below impermeable beds." He mentions also that a few American geologists(b) have used the term, and concludes by recommending that the expression "'phreatic water' be regarded as a synonym of ground-water--including all water in the zone of saturation." However, Meinzer makes no distinction which recognizes a zone of complete capillary-saturation, for on a succeeding page he describes ground-water as that which supplies springs and wells. Furthermore, he provides a term, "vadose" or "suspended subsurface water," for water in the zone of aeration, a term which might well be extended to include water in the zone of complete capillary-saturation. [References: (a) Daubree, Les eaux souterraines a l'Epoque actuelle, v. 1, p. 19, Paris, 1887; (b) R. Hay, Artesian and underflow investigations, 52nd Cong., 1st session, S.Ex. Doc. 41, pt. 3, p. 8, 1893; W. J. McGee, Potable waters of the Eastern United States, U.S. Geol. Surv., 14th A. Rep., pt. 2, pp. 15-16, 1893; and R. A. Daly, Genetic classification of underground volatile agents, Econ. Geol., v. 12, pp. 495-499, 1917.]

Other writers, including Zunker(a), Körner(b), Kozeny(c), and Nemenyi(d), describe the zero-pressure line as the "ground-water" line, the "free-water line," or the "apparent ground-water level." In a paper by Wyckoff, Botset, and Muskat, the upper boundary of the zone of complete capillary-saturation is called the "capillary free-surface." [References: (a) F. Zunker, Handbuch der Bodenlehre, v. 6, 1930; (b) B. Körner, Erforschung der physikalischen Getsetze nach velchen die Durshsickerung durch eine Talsperre oder durch den Untergrund stattfindet, ler Congres des Grands Barrages, Stockholm, 1933; (c) Kozeny, Ueber Grundwasserbewegung (concerning ground-water flow), Wasserkraft u Wasserwirtschaft, No. 5 et. seq., 1927; and (d) P. Nemenyi, Die Grundwasserbewegung (ground-water flow), Handbuch der techn. u. phys. Mechanik, v. V, p. 1116, 1930.]

Although it is not entirely clear whether Meinzer intended to comprehend the zone of capillary-saturation within the term ground-water (since he states both that ground-water supplies springs and wells, and that ground-water should include all the water in the zone of saturation), it is fair to conclude that the term is most generally used in the sense of free-water under zero or positive pressures. To describe all water below the zero-pressure line as "phreatic" water appears even more justifiable, for the word being less known will not be subject to ambiguous interpretation resulting from conflicting usage. Its general definition (Webster), of or pertaining to wells, may be thought of as suggesting that the phreatic surface is the surface indicated by the water-level in a well when the well is not driven so deeply as to intersect regions at different potentials.

This precise usage of the term appears in an article by G. H. Van Mourik Broksman and A. S. Buisman(a), in which the line of zero-pressure in a model earth-dam is clearly illustrated as the "phreatic" line. [Reference: (a) Waterspanningen in Dijken en Dammen, De Ingenieur, v. 49, n. 32, August 10, 1934.]

(d) Conclusion--In view of the foregoing, it is proposed that subsoil-waters be distinguished as to whether they lie within (1) the zone of aeration, (2) the zone of complete capillary-saturation, or (3) the zone of positive hydrostatic pressure. It is further proposed that the line of zero-pressure representing the boundary between zones (2) and (3) be known as the phreatic line, and that the boundary between zones (1) and (2) be known as the saturation-line. Alternate expressions describing the three zones might be equally acceptable as follows: (1) Zone of aeration = zone of partial capillary-saturation; (2) zone of complete capillary-saturation; (1) and (2) combined, capillary-zone - zone of suspended subsurface-water = zone of vadose water = zone of negative hydrostatic pressure; (3) zone of positive hydrostatic pressures = zone of phreatic water = free ground-water zone = gravity-zone. It is thought that the term ground-water should only be used when properly qualified or when further distinction is of no significance.

(2) Memorandum by C. A. Taylor, H. F. Blaney, and W. W. McLaughlin, Bureau of Agricultural Engineering, United States Department of Agriculture, to Charles H. Lee, Chairman, in reply to certain comments on terminology by Dr. F. J. Veihmeyer. The comments were sent by letter addressed to Mr. Blaney under date of April 11, 1935. The terms under discussion were used in the paper "The wilting-range in certain soils and the ultimate wilting-point" by C. A. Taylor, H. F. Blaney, and W. W. McLaughlin.

The following comments by Dr. Veihmeyer are quoted from Mr. Lee's letter of April 11, 1935:

"Dr. Veihmeyer makes certain comments on terms which I believe were suggested by Mr. Taylor of your office. Before making any modifications in the Committee definitions as now worded I would appreciate having your reaction to his comments. The latter are as follows:

"'The term permanent wilting-percentage was first used in California Agricultural Experiment Station Bulletin 479 (Irrigation experiments with peaches in California, 1929), where it was emphasized that the permanent wilting-percentage is not an exact point, but is represented by a small range on the curve showing the energy required to extract water from soil as a function of the moisture-content. Since this function is a continuous one and since the degree of wilting of plants is difficult to determine, it seems futile to attempt to select another point on the curve such as the ultimate wilting-point, so close to the permanent wilting-percentage. We also believe that the ultimate wilting-point as defined will vary with factors other than the soil. For these reasons, the term wilting-range may be of little use.

"'The term readily available water is defined by using the term 'wilting-coefficient' which has not been defined in the report. The definition does not agree with that given in California Agricultural Extension Service Circular 50 (Essentials of irrigation and cultivation, p. 7), where it was first used. The distinction between available and readily available water seems to us useless in view of the objection to the use of ultimate wilting-percentage given above.'"

As stated by Dr. Veihmeyer, he first used the term permanent wilting-percentage in 1929. In 1912 Briggs and Shantz defined the wilting-coefficient as the moisture-content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in their moisture-content as the result of a deficiency in the soil-moisture supply. Veihmeyer in his definition of permanent wilting-percentage states that it "represents a narrow range in soil-moisture content within which wilting takes place" (Calif. Agri. Exten. Circ. 50). Hence his determinations of permanent wilting-percentage are made at the end of the range of wilting he has chosen as standard for his experiments. It is therefore lower on the curve showing the energy required to extract water from soil as a function of the moisture-content than the first point given in the definition of Briggs and Shantz.

In our work with irrigated orchard crops, we have found that the definition of Briggs and Shantz for wilting-coefficient, or wilting-point as it is commonly referred to, comes nearest to fitting the fairly definite field soil-moisture content at which there is a pronounced and somewhat abrupt reduction in rate of loss of soil-moisture and in plant-response. In straight-furrow irrigated orchards the moisture-content of the soil may drop quite regularly and at a fairly constant rate until about the wilting-point as defined by Briggs and Shantz. Along the dry unirrigated tree-lines there will be a continued slow loss of moisture and eventually the moisture-content may drop as low as the permanent wilting-percentage as defined by Veihmeyer.

With native Xerophytic vegetation we found that the moisture-content of the soil would be extracted to a point below Veihmeyer's permanent wilting-percentage and finally or ultimately remain at this level of soil-moisture. We chose to call this the ultimate wilting-point and found it a useful base from which to calculate the total available moisture that might be withdrawn by the plants.

Veihmeyer's permanent wilting-percentage represents a moisture-condition below the first point as defined by Briggs and Shantz and above the ultimate wilting-point as defined by Taylor, Blaney, and McLaughlin. Hence it lies somewhere within the wilting-range and because of this we have found little practical field-application for the permanent wilting-percentage. Irrigated crops suffer for lack of water and their yield is reduced before the permanent wilting-percentage is reached and native plants draw the soil-moisture content down below this point.

In Dr. Veihmeyer's comments given in Mr. Lee's letter of April 11, he states, "...the term wilting-range may be of little use," and again, "The distinction between available and readily available water seems to be useless." However, we find that the wilting-range may represent as much as 25 per cent of the total water available for plant-use. This, we feel, is too large a range to ignore. Dr. Veihmeyer admits in his definition that there is a wilting-range. The logical thing to do is to use the term so that the casual reader, or the farmer who would make application to field-practice, gains a proper conception of wilting as a range and not as a point or a percentage.

Several cases have been observed where reduced yields and injury resulted when orchardists attempted to dry the soil down to a wilting-point determined with sunflowers. The difficulty lay in the fact that these growers had the conception that all moisture above the permanent wilting-percentage that they had determined with sunflowers was readily available water and that the trees should dry the soil down to this point without suffering. This, they found, was not correct.

To illustrate the wilting-range Figure 1 is submitted, showing the moisture-extraction curve for a Meyer clay-adobe soil for Medford, Oregon. Each sample can contained 500 grams of

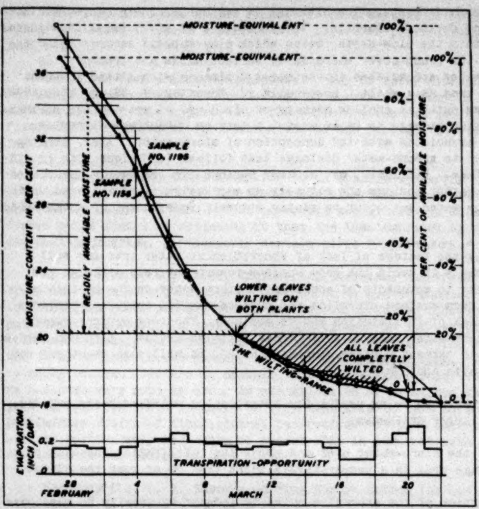

FIG. 1—RATES OF EXTRACTION OF SOIL-MOISTURE BY SUNFLOWER' PLANTS FROM CLAY-ADOBE SOIL IN SEALED CONTAINERS FROM THE MOISTURE-EQUIVALENT DOWN TO THE POINT OF COMPLETE WILTING OF ALL LEAVES ON THE PLANTS, FEBRUARY TO MARCH, 1933

soil and a single sunflower-plant. The cans were weighed each morning. In 10 days the moisture-contents were reduced from 37 and 39 per cent to 20 per cent. On the morning of March 10 it was noted that the lower leaves were wilted on both plants. By March 20 all leaves completely wilted on sample 1195 and a like condition was attained on March 22 on sample 1156. Water was then added to the soil and the plants revived and continued to grow.

It is obvious from Figure 1 that wilting takes place over an appreciable range in soil-moisture content and that through this range there is a marked reduction in rate of extraction of moisture. Lewis, Work, and Aldrich found marked reduction in rate of growth of pears on this soil whenever the soil-moisture content on certain of their plots remained within the wilting-range for any appreciable length of time. We feel that recognition of this wilting-range is necessary for the interpretation of plant-responses to soil-moisture conditions. In the application of experimental results to field-irrigation practice it is essential that the wilting-range be delimited before the range of readily available moisture can be determined. The ultimate wilting point can be readily determined and serves as a useful base in determining the wilting range.

(3) Discussion by C. R. Hursh, Appalachian Forest Experiment Station, United States Forest Service, Asheville, North Carolina.

Storm-water and absorption

The following discussion is confined to conceptions of storm-water as a basis for comparing absorption of water into different soil-profiles (Appendix A, List of terms with definitions, Committee on Absorption and Transpiration, 1934-35, Transactions, Amer. Geophys. Union, 16th Annual Meeting, pp. 396-404, 1935.)

Present interest in studies of infiltration of water into different soil-profiles has led to the intensive study of small enclosed plots or other small drainages not supporting continuous stream-flow. A terminology for expressing ideas of absorption and infiltration of water into the soil together with other factors of water recharge and discharge on small drainages is not available at present except as adapted from hydrological terms of established usage.

In the list of terms and definitions in the above reference, the five terms given under the heading of runoff do not present a complete conception of the accumulation and disposition of storm-water resulting from lack of infiltration of precipitation into the soil. When rate of rainfall is greater than the rate of its infiltration, storm-water accumulates on level ground until such time as the balance between rain-intensity and rate of infiltration is reversed, so that further infiltration will permit the accumulated storm-water to enter the soil. On sloping land, gravity produces a movement of accumulated storm-water, which is actually surface-stormflow. On some areas infiltration may be rapid only for the upper horizons of the soil-profile. This absorptive layer of the soil-profile may extend only for a few inches or it may extend to the bottom of the A-horizon. Beneath this absorptive layer an impervious subsoil may occur. When such conditions obtain, very little surface-stormflow may be apparent, although a considerable amount of storm-water moves from the area at a rate much more rapid than the usual ground-water flow. Such water then becomes subsurface-stormflow although it may subsequently become surface-stormflow within the minor surface drainage-channels. This condition is often found in depleted fields where sand accumulates within the plow-depth, below which clay-subsoil occurs. Also the condition may occur under forest- or brush-cover where sandy surface-soils are present. In these cases, considerable storm-water accumulates in the minor drainages with little apparent surface-stormflow throughout the area as a whole. Lowdermilk (J. Forestry, v. 32, p. 534, 1934) has referred to this form of storm-water as shallow seepage or discharge of wet-weather springs. The writer does not consider shallow seepage to be as useful a term as subsurface-stormflow, inasmuch as it is not so closely associated with the conception of storm-water. Also, shallow seepage is sometimes used to refer to ground-water drainage that follows impervious rock or other layers lying close to the surface. Similarly, wet-weather springs are frequently associated with perched water-tables. Wet-weather springs are actually an expression of established drainages, whereas subsurface-stormflow water may occur on slopes entirely independent of established drainages.

For the purpose of discussing the factors of lack of absorption of water into any soil-profile, it may prove to be desirable to avoid the term surface-runoff entirely although the term is now being used in referring to movements of accumulated storm-water on the surface of the ground. By substituting the term surface-stormflow for surface-runoff, confusion of ideas appertaining to infiltration or lack of infiltration may be avoided. The term surface-runoff has been used for the surface-stream water from an established drainage-system. Although surface-runoff may be adopted to be used to express surface-stormflow water, it will also doubtless continue to be used by some writers with another meaning.

The following terms are suggested as being useful for interpreting water recharge and discharge from both small plots and larger drainages:

Stormflow is that portion of the storm-water over and above the infiltration-capacity of the ground which leaves the drainage-area in a comparatively short time on or near the surface.

Surface-stormflow is that portion of the stormflow which is induced by gravity to move over the surface of the ground.

Storm-seepage or subsurface-stormflow is that portion of the stormflow which infiltrates into the surface-soil but moves away from the area through the upper soil horizons at a rate much in excess of normal ground-water seepage.

Surface-runoff is that portion of the runoff leaving a drainage-area through surface-channels as streams.

Subsurface-runoff is that portion of the runoff leaving a drainage-area as subsurface-flow associated with stream-channels.

Runoff is the sum stream-discharge from a drainage including both surface- and subsurface-runoff.

Ground-water flow is that portion of the precipitation which has been absorbed by the ground and has become part of the ground-water, ultimately being discharged as spring- and seepage-water into the stream-channels and leaving the drainage as runoff.

REPORT OF THE COMMITTEE ON RAINFALL AND RUNOFF, 1935-36

L. K. Sherman, Chairman

The Chairman, in a letter to members of the Committee and others, stated as follows:

"(1) Opportunity for public discussion of important hydrologic papers presented before the American Geophysical Union has not been furnished. Such papers require advance distribution to enable a satisfactory review to be made, and the present facilities of the American Geophysical Union do not permit this. The value of these papers would be greatly enhanced by written discussion.

"(2) The above comment also applies to many other papers and publications presented during the year as separates or in works which offer no opportunity for open discussion. A few notable exceptions exist, such as the Proceedings of the American Society of Civil Engineers and certain journals.

"(3) Therefore, the annual report of the Committee on Rainfall and Runoff will include an Appendix devoted to short discussions of papers or publications which have appeared during the past year."

There has been a generous response. Many of these discussions are valuable separate papers. Two which discuss United States Geological Survey Water-Supply Papers 771 and 772 are included as appendices of this report: A, "The Hayford method versus the (Sherman) unit-graph" by J. A. Folse; B, "Discussion of Publication 400 of the Carnegie Institution of Washington" by Merrill Bernard.

Mr. Bernard also calls attention to an article appearing in the Engineering News-Record (february 17, 1927, p. 270) entitled "Rainfall-runoff analysis in storm-sewer design" by John A. Rousculp of Columbus, Ohio. "The paper did not attract my attention at the time it was published but I find upon reviewing it that the idea embraced by it is similar in some respects to the unit-hydrograph, particularly certain steps in procedure."

Mr. T. T. Knappen, Chief, Engineering Division, Muskingum Flood-Control Works, writes: "Possibly the most troublesome problem which we had to contend with in the hydraulic design of the Muskingum Reservoir-System was the effect of valley-storage on our reservoir-filling computations. We found, in working from hydrographs at the dam-sites, that a considerable correction was necessary to produce the hydrograph of inflow to the reservoir. I pointed this fact out in my article in the January issue of Civil Engineering. Early in our studies, we attempted to apply constant factors to produce this inflow-hydrograph. Our detailed studies showed us that we had been very much in error in our selection of constants for this purpose. This whole subject is one upon which it would be very desirable to have more information, particularly for the preliminary design of flood-control reservoirs. We have been trying to develop data from recent storms, particularly the storm of August 1935 in the Muskingum Valley, to check the unit-graphs developed in the design of this project."

Appendix C by L. K. Sherman on "The Horton method for determination of infiltration-rates" discusses R. E. Horton's Bulletin 101.

Colonel C. R. Pettis has made further studies on the application of his runoff-formula which appeared in the issue of the Military Engineer for March-April 1936. The Chairman offers the following discussion:

The Pettis Formula, of the form $Q = C(PW)^{1.25}$, is an expression for the peak-rate of runoff in cfs, wherein W is the mean width of the basin or area divided by flood-length of channel, and P is the depth of rain falling in 24 hours during a 100-year frequency storm, falling over the entire basin. P is about two-thirds of the total storm-rainfall. The formula is basically a rational runoff-formula, inasmuch as there are included the area and shape of the basin and the intensity of rainfall. I agree with Grunsky's statement to the effect that "no runoff-formula excluding the element of rain is worth while." The Pettis Formula is empirical, or at least statistical, in the use of coefficient C and the use of the exponential 1.25. The formula agrees closely with a large number of observed peak-rates of flood-runoff. This comparison made by Colonel Pettis evidently represents a large amount of careful investigation. It is a valuable compilation and, more than any one argument, supports the reliability and usefulness of the width-formula.

In selecting the value of P, it is obvious that the maximum of observed rainfall-intensity at a single station in the basin should be reduced in accordance with the size of the basin.

Slope--The Pettis Formula does not include the factor of slope. Colonel Pettis justifies this omission by several lines of reasoning, namely, by comparison (p. 3) of several velocities from different sized basins in Ohio, New York, and Pennsylvania, wherein the average flood-velocity from these different sized basins was $V = (PW)^{0.25}$ ft/sec of water cross-section $A = 310\ PW$ square feet. The question arises: How much did each value of A vary from the average? May not the governing slopes in these four cases have been practically identical? May not the coefficient C be 310 for such slopes, and something else for flatter slopes?

Colonel Pettis indicates that extremes of slope (p. 6) and valley-storage (p. 5) do reduce the peak-rates of runoff, or what is the same thing, do affect the value of C. This is in accord with my observations, namely, that the typical or unit-hydrographs reflect the slope and all other physical characteristics of a drainage-basin. Colonel Pettis points out the fact that all natural streams cut and maintain channels of a definite cross-section and grade, dependent principally upon the average annual rates of flow. Be that as it may, some streams, like the Delaware, carry their floods largely within their banks, and other streams, like the Illinois, commonly spread over a wide flood-plain.

Seepage--I concur with Colonel Pettis (p. 4) that in the case of 100-year storms or floods, the seepage-factor is generally immaterial, and that the frequencies of 100-year floods and 100-year storms are nearly identical. This is not true for smaller storms of greater frequency. In some areas, notably Minnesota and upper Wisconsin, the total storm-runoff, as well as peak-runoff, is generally less than 50 per cent of the storm-rainfall.

Time of concentration--The statement (top p. 11) "At the crest of the flood the effective rain is running off at G at the same rate as the average rate at which it fell from the clouds" is the condition under the rational theory at time of concentration, and with an impervious surface. There are many angles to the factor "time of concentration." Colonel Pettis has discussed some of them. A storm of duration T (the concentration-period) is almost always composed of a long period of small or moderate rain-intensities combined with a shorter period of high-intensity rainfall. It is this combination of rainfall that produces the flood-peak. Minor variations of rain-intensity are ironed out by the effect of storage and time of transit on runoff. The rational method does not apply to large natural areas. I think Colonel Pettis' comments on pages 5 and 10 support this.

My conclusions are as follows:

(1) The Pettis Width-Formula, for peak-rates of 100-year frequency runoff, is useful and reliable. It is superior to any similar semi-empirical formulas or to the "rational method" when applied to large natural basins.

(2) The Formula is especially useful in cases where no recorded data are available for determining the unit-hydrograph or basic relation between rainfall and runoff. In cases where the data are available the unit-procedure, although longer, is more reliable.

(3) The use of the Pettis Formula should be restricted to the limitations prescribed by the author, namely: (a) It applies only to peak-rates of runoff of 100-year frequency--it does not apply to lesser storms; and (b) it does not apply to streams of flat slopes and large valley-storage.

(4) The Pettis Formula furnishes a simple and rapid check upon more detailed methods of computing the peak-rates of flood-runoff.

Colonel Pettis presents the following statement to the Committee:

"Factors affecting flood-probabilities--The writer has made a study of all major floods in the United States for which he had official records, the limits of drainage-area considered being 100 square miles to 100,000 square miles. The following statements seem to be either justified by the evidence, or else the most reasonable hypotheses which are consistent with the evidence.

"Cloud-bursts are storms affecting relatively small areas, in which the precipitation is well above the general storm-average for the region. It is believed that the danger for any stated area will be so remote that flood-probabilities will be but slightly affected for areas over 100 square miles; and the danger for areas greater than 1000 square miles will be negligible.

"The major factors affecting 100-year runoff are: (1) Rainfall, represented by rainfall-index P; (2) shape of area, represented by average width of area W; (3) general humidity or aridity, which affect seepage, as reflected in coefficient C; (4) slope, only in prairie-regions, where V is less than Mr. Lacey's non-silting value (Min. Proc. Inst. C. E., v. 229); and (5) certain unusual shapes, in which the basin is unusually wide or unusually narrow near the gaging-station.

"Certain minor factors are: (1) Effect of length of basin for same width; (2) valley-slopes; (3) channel-storage; and (4) time-variations in rainfall. The minor factors are probably accompanied by compensating conditions, so that effects are not apparent in statistical results.

"The Miami storm-charts are on the whole quite accurate and adequate although they were made twenty years ago.

"Mr. Bernard's rainfall-relations (Trans. Amer. Soc. C. E., 1932) seem consistent with other data.

"The CIA-type of formula is correct in principle; if properly applied it is equivalent to the width-formula.

"The Foster probability-method is mathematically exact, but seepage is a major factor in most floods less than the probable 100-year flood, and caution should be used in extrapolation from short-time records.

"For 100-year storms and greater, seepage is near a minimum for the locality; for the areas considered, the 1000-year rain will be about 20 per cent greater than the 100-year rain; and the 1000-year flood will be about 20 per cent greater than the 100-year flood.

"The principle of the unit-graph method can be developed to build up a hydrograph from the hydrographs of tributaries, in addition to the present use of this method.

"All the elements of the cross-section of a stable channel with uniform flow are determined by the discharge and the nature of bed material (Lacey, reference above).

"Some coordination has been discovered between flood-flows and astronomical cycles; but no long-time trends have been discovered."

Walter J. Parsons Jr., United States Engineer Office, St. Paul, Minnesota, discusses in Appendix D Water-Supply Paper 772, "The use of long-term runoff-records in the detection of secular trends."

S. L. Moyer presents the following:

"Statistical methods--The current discussions of the subject of hydrology seem to take it for granted that statistical methods are of doubtful validity. This trend of thought, perhaps, is a natural reaction from the previous elaborate attempts to extend the theory of precision to cover the whole field of probability. The amazing scope of this unwarranted extension, in view of the simple fundamentals that demonstrate its error, is a sad commentary on human intelligence, but, on the other hand, it may be wise to pause and consider the current inclination to reject the whole subject and reflect on the possibility that this, likewise, may be fully as absurd as the previous views.

"I, for one, firmly believe that, after the wreckage has been cleared away and after the subject has been reconstructed in accord with the facts of nature, statistical methods are fairly certain to become highly valuable as a research-mechanism. It seems reasonable to say that, in the light of general experience, a redesign of the tool is in order rather than rejection of the whole idea."

On the subject of rainfall, C. H. Eiffert, Chief Engineer, Miami Conservancy District, advises: "The report on rainfall of the eastern United States is being revised at the present time. The final copy is being typed now and as soon as it is ready for distribution an announcement will be made."

T. F. Mavis and D. L. Yarnell presented a paper appearing in the Proceedings of the Iowa State Engineering Society entitled, "Frequency of intense rainfall in Iowa" (see also Eng. News-Record, August 8, 1935.)

An important publication by D. L. Yarnell was issued in August, 1935, by the United States Department of Agriculture (Misc. Pub. 204) on "Rainfall-intensity--Frequency-data." It contains numerous isohyetal maps of the United States.

This work is discussed in a contribution to the Committee by Merrill Bernard in Appendix E. Montrose W. Hayes may present the subject of rainfall-data in a separate paper.

Robert E. Horton, under date March 4, 1936, has prepared a paper (not yet published) entitled "Maximum daily rainfall." He states in part:

"Recently issued climatic summary of the United States for the sections covering Kentucky, Pennsylvania, Nevada, Arkansas, and Kansas, give, for every long-record rainfall-station, the maximum rainfall for a record-day in each month of the year.

"Monthly data for each station were tabulated with the following column-headings: (A) Greatest recorded rainfall for a record-day; (B) average monthly rainfall for each month; (C) average number of rainfall-days for each month; and (D) average rainfall-amount per record-day = B/C.

"It was found that the ratios A/D were of the same order of magnitude and frequency and that the maximum ratio was about the same for stations in all the different sections, indicating that the ratio of the maximum record-day rainfall to the average amount per rainfall-day (0.01 inch or over) is substantially the same throughout the whole country even though there are wide variations in the average amount per rainfall-day."

The Chairman merely notes this important research here. The paper should be published.

With further reference to Water-Supply Papers 771 and 772, Gordon R. Williams furnishes the following:

"Description of the hydrologic studies conducted in New York City--Through the efforts of Thorndike Saville, Associate Dean, College of Engineering, New York University, an appropriation of about $55,000 was obtained from the Works Progress Administration for New York City for hydrologic studies with particular emphasis on flood-flows. The work was to be a continuation of the studies made by the Geological Survey in cooperation with Water-Planning Section of the National

Resources Committee, the results of which have been published in Water-Supply Papers 771 and 772. The Geological Survey and the Soil-Conservation Service agreed to furnish funds and personnel for technical supervision of the project. Gordon R. Williams has had immediate direction of the work. Five separate studies have been conducted as follows:

"The first study was designed to make further investigations into the application of statistical methods to the analysis of flood-flows. Eight of the longest records of flood-flows were analyzed by several methods with the express purpose of bringing out the characteristics and limitations of the methods. Special emphasis was placed on the method developed by H. Alden Foster and the more recent method developed by Professor J. J. Slade. The results obtained so far are exceedingly interesting and it is hoped that some progress has been made in revealing the characteristics of statistical methods.

"The second study carries out a recommendation of the American Society of Civil Engineers' Committee on Flood-Protection Data in that it is a tabulation of flood-stages for gage-height records maintained by the United States Weather Bureau and United States Engineers.

"A third study somewhat similar to the one just mentioned is a tabulation of maximum discharges for all stations which have been maintained by the United States Geological Survey and its cooperation agencies. It is expected that determinations of flood-discharges from other reliable sources will also be included. This study, which is rapidly nearing completion, will include available information on maximum flood-discharges at about 6000 gaging-stations and measuring-points in the United States.

"The fourth study is a compilation of annual water-losses for river-basins in various parts of the United States. This study was entered into with a full realization of the difficulties involved, especially in the determination of mean annual rainfall on an area. Accordingly, only those basins where rainfall-data were relatively plentiful and where stream-flow data represented natural runoff were selected for computations. Results from over a hundred areas have been obtained and appear to be quite consistent.

"The fifth study is a bibliography which is being made for the Soil-Conservation Service. It is confined to papers in foreign languages dealing with erosion and silt-movement. Abstracts are being made of the more important papers."

In addition to the foregoing we note the following recent papers on rainfall or runoff: (a) C. S. Jarvis, "Flood-stage records of the River Nile" (Proc. Amer. Soc. C. E., August 1935)--to the Chairman this record indicates that nature's average, for at least 3000 years, is a constant; (b) S. T. Harding, "Variation in runoff in California streams" (Civ. Eng., November 1935); (c) Thorndike Saville, "National water-resources studies" (Eng. News-Rec., February 6, 1935). Also in the same publication: (d) Montrose Hayes, "Weather in 1935", and (e) John C. Hoyt, "Recent water-records and trends."

To complete the work of the Chairman, as historian, record is here made of the occurrence of extensive floods in Eastern United States during 1935-36, namely: (a) July 7-8, 1935, in Central New York (Eng. News-Rec., p. 319, September 5, 1935; see also records United States Weather Bureau and United States Geological Survey, and report Corps of Engineers, United States Army); (b) August 6-7, 1935, in Muskingum Valley, Ohio (Eng. News-Rec., November 14, 1935); (c) March-April, 1935, record-floods in New England, the Susquehana Basin and the Upper Ohio Basin.

It is important that studies be made on the meteorology and hydrology of these floods. We understand that a Public Works Administration allocation of funds for this purpose has been made.

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APPENDIX A--THE HAYFORD METHOD OF ESTIMATING SURFACE RUNOFF VERSUS THE SHERMAN ("UNIT-GRAPH") METHOD

J. A. Folse

(1) Introductory--The primary thesis of this discussion is three-fold, namely: (a) To show that the basic principles underlying the so-called "unit-graph" method of estimating surface runoff appearing in an article by L. K. Sherman (Stream-flow from rainfall by unit-graph method, Eng. News-Rec., April 7, 1932) in 1932 appeared in Publication 400 (J. A. Folse, A new method of estimating stream-flow based upon a new evaporation-formula, Washington, 1929) of the Carnegie Institution of Washington; (b) to show that the method of applying the principles involved in the latter reference is more rigorous as well as more widely applicable, and hence, obviously, superior to the mere graphical method; and (c) to point out that the principle involved had been in use since 1911 on the computations and studies involved in Publication 400.

(2) Surface-runoff to stream B at Wagon Wheel Gap, Colorado--The surface-runoff to this stream as given by equation 86 (p. 177 of Pub. 400), which is rewritten here for convenience, is

$$1.40\ r_{f_1} + 1.43\ r_{f_2} + 1.61\ r_{f_3} + 1.64\ r_{f_4} + 14.0\ r_{f_5} + 8.24\ r_{f_6} + 3.11\ r_{f_7} = D_F \qquad (1)$$

in which r_{f_1} = increase in storage above the ground-surface on the current day; r_{f_2} = increase in storage on the preceding day; r_{f_3} = increase in storage on the day before the preceding day; r_{f_4} = increase in storage on the next preceding two days; r_{f_5} = increase in storage on the next preceding four days; r_{f_6} = increase in storage on the next preceding eight days; r_{f_7} = increase in storage on the next preceding sixteen days; r_{f_1} to r_{f_4} are in units of 0.01 inch of depth and r_{f_5} to r_{f_7} are expressed in 0.1 inch of depth; and D_F is the "flood-flow" or that part of the total stream-flow due to surface-runoff, in units of 0.001 cfs.

This is the equation of a curve to which Sherman's "unit-graph" corresponds exactly except (a) that the ordinates are expressed in 0.001 cfs instead of cfs, (b) that the increases in storage (r_{f_1}, r_{f_2}, ...) are in 0.01 inch of depth instead of 1.0 inch of depth, (c) that it covers a time-interval of 33 instead of 11 days, (d) that it is derived analytically instead of graphically, and (e) that the method of computing r_{f_1}, r_{f_2}, ... is different--more rational--than in Sherman's method. More complete explanations of these points of difference are hereinafter given in the order stated. The graphical representation of (1) is shown on Figure 1 in units stated in the following paragraph.

(3) If D_F is expressed in cfs and r_{f_1}, r_{f_2}, r_{f_3}, ... are expressed in inches of depth on the watershed, (1) becomes

$$0.14\ r_{f_1} + 0.143\ r_{f_2} + 0.161\ r_{f_3} + 0.164\ r_{f_4} + 0.140\ r_{f_5} + 0.0824\ r_{f_6} + 0.0311\ r_{f_7} = D_F \text{ cfs} \qquad (2)$$

in which r_{f_1}, r_{f_2}, ... r_{f_7} are in inches of depth. This equation is now in the same units used by Sherman, but in plotting it on the accompanying graph the ordinates are multiplied by 10,000.

(4) Equation (2) may be converted to other useful units. By multiplying the coefficients of r_{f_1}, r_{f_2}, r_{f_3}, ... r_{f_7} by 11.9 approximately (as shown on p. 176 of Pub. 400), one obtains

$$1.67\ r_{f_1} + 1.70\ r_{f_2} + 1.92\ r_{f_3} + 1.95\ r_{f_4} + 1.66\ r_{f_5} + 0.98\ r_{f_6} + 0.37\ r_{f_7} = D_F \qquad (3)$$

in which D_F is in units of 0.001 cfs, r_{f_1}, r_{f_2}, r_{f_3}, ... are in units of 0.01 inch of depth on the watershed, and the coefficients now express the percentage of the change in storage above ground which reaches the stream on each day. For example, for any net increase in storage above ground, 1.67 per cent of it reaches the stream on that day, 1.70 per cent on the following day, and so on, until after the lapse of 33 days, 29 per cent has been delivered to the stream by surface-travel. It is this form of expression for the runoff-curves which was adopted for graphical representation on Plate 8 of Publication 400, where it may be noted that (3) is shown in the upper, dashed curved. The corresponding surface-runoff curve for stream A is shown solid on Plate 8, and its equation--in the units used in (1)--is equation (87) of page 178 of Publication 400.

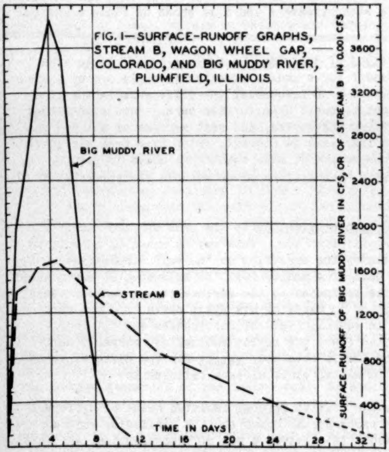
FIG. 1—SURFACE-RUNOFF GRAPHS, STREAM B, WAGON WHEEL GAP, COLORADO, AND BIG MUDDY RIVER, PLUMFIELD, ILLINOIS

(5) Interpretation of equations (1) to (3)--These equations mean that the surface-runoff to the stream is a linear function of the increase in storage above the ground-surface and that for any such

increase in storage on stream B watershed it will require 33 days for 29 per cent of the increase in surface-storage to be delivered to that stream. It is specifically stated in various passages of Publication 400 that the surface-flow curve for any stream, or its analytical expression, is constant, but that different streams will have different characteristics, as expressed in their equations and curves. The basic principles involved are the same, therefore, as those subsequently used by Sherman, with the exceptions to be noted.

(6) Surface-runoff to Big Muddy River at Plumfield, Illinois--The surface-runoff to this stream as derived by Sherman is shown graphically in Figure 6 (p. 504) of his article referred to above, and is reproduced in Figure 1. It may be expressed analytically as follows:

$$1,950\ r_{f'_1} + 2,590\ r_{f'_2} + 3,370\ r_{f'_3} + 3,870\ r_{f'_4} + 3,540\ r_{f'_5} + 2,470\ r_{f'_6}$$
$$+\ 1,310\ r_{f'_7} + 610\ r_{f'_8} + 350\ r_{f'_9} + 160\ r_{f'_{10}} + 80\ r_{f'_{11}} = D_F \qquad (4)$$

in which D_F is the surface-runoff in cfs, and $r_{f'_1}$ = increase in storage above ground-surface on current day, $r_{f'_2}$ = increase in storage above ground-surface on preceding day, $r_{f'_3}$ = increase in storage above ground-surface on next preceding day, etc., all expressed in units of one inch of depth on the watershed. The coefficients of $r_{f'_1}$, $r_{f'_2}$, ... are taken from column 5 of Table 1 of Sherman's article. Specific values of $r_{f'_1}$, $r_{f'_2}$, ... as computed by Sherman for this River are shown in column 5 of his Table 2 headed "Runoff, in." Equation (4) may be converted to percentages by dividing each coefficient by 20,300 and multiplying by 100, thus

$$9.6\ r_{f'_1} + 12.8\ r_{f'_2} + 16.6\ r_{f'_3} + 19.1\ r_{f'_4} + 17.5\ r_{f'_5} + 12.2\ r_{f'_6}$$
$$+\ 6.5\ r_{f'_7} + 3.0\ r_{f'_8} + 1.7\ r_{f'_9} + 0.8\ r_{f'_{10}} + 0.4\ r_{f'_{11}} = D_F \qquad (5)$$

in which D_F is in cfs, $r_{f'_1}$, $r_{f'_2}$, ... are in inches of depth, and the coefficients express the per cent of any increase in storage above the ground-surface which reaches the Big Muddy River on each day during a 11-day period. For example, for an increase in storage of one inch of depth on any day, 9.6 per cent or 0.096 inch reaches the Big Muddy River on that day, 12.8 per cent or 0.128 inch reaches it the following day, etc., so that after the lapse of 11 days, 100 per cent or one inch will have reached the stream, according to Sherman. (It is extremely doubtful that this is true, since on streams A and B only 19.0 per cent and 29 per cent, respectively, reach those streams after the lapse of 33 days. But to prove the contrary would require a great deal of computation.) The graphical representation of (5) is the same as that of (4) shown in Figure 6 of Sherman's article if the ordinates to the latter curve are each divided by 203, and in this form the Big Muddy River is directly comparable with streams A and B as shown on Plate 8 and in equations (86) and (87) of Publication 400.

(7) The analytical versus the graphical method of deriving the surface-runoff curve--The difference in the units in which the surface-runoff curve and/or equation is expressed by Sherman in comparison with that in Publication 400 is of minor consequence; the difference in the time-intervals covered is more important, but will not be dwelt upon further here. More significant, still, is the difference in the methods of deriving the curves, and most serious of all are the differences in the methods of computing the net increases in storage, which have been designated r_f and $r_{f'}$ in the Hayford and Sherman methods, respectively, with subscripts added to specify the time-interval covered by each. Outlining, briefly, the difference in methods of derivation of the curves, it is claimed that

(8) Sherman's unit-graph is virtually a first approximation to the true surface-runoff curve, as judged by the procedure followed in Publication 400. This may be shown by an outline of the method of deriving (1) for stream B, assuming the base-flow or "normal" stream-flow to be known. For any isolated rain, such as that of October 4 and 5, 1911, on Watershed B, Wagon Wheel Gap, Colorado, the first step was to estimate the ordinates to the surface-flow equation. This was done in the manner Sherman subsequently adopted in deriving his final curve, and the particular values so estimated for stream B are shown in equation (81) of Publication 400 (p. 173). When these are substituted in the general equation (79), the strict analogy of Sherman's unit-graph to the surface-runoff curve in Publication 400 is obtained, except for the differences as to method of estimating base-flow, differences in units, etc., already referred to.

(9) The next step is to apply general equation (79) to several isolated rains of different intensity (not merely one, as in the unit-graph process), as shown for the particular rain of October 4-5, 1911, on page 173 of Publication 400. This leaves a set of discrepancies, -F, which

are substituted in equation (78), thus obtaining a set of corrections to the first approximation to the flood-flow equation. The set of corrections so obtained for stream B is shown in equation (84) on page 175. It is based upon 166 days of flood-flow produced by several rains in the summers of 1911, 1912, and 1913.

(10) *Flood-flow curve of Publication 400 a weighted mean*--When the computed corrections by (84) are added to the assumed curve of (81), the final flood-flow curve of (85) is obtained. This is smoothed as depicted on page 176, resulting in (1), already presented above. This final flood-flow curve is obviously superior to the one obtained graphically because: (a) It is based upon several instead of one rain and its after-effects; (b) these rains, of different intensities, and occurring in different calendar months, are automatically weighted by the least-square process giving a final curve which is the best attainable from the given data and of more general application; and, of much greater importance, (c) the curve more nearly represents the facts because of a better method of estimating the losses by evaporation, transpiration, etc.

(11) *Method used in computing increase in net storage above ground-surface*--All of the preceding equations express the surface-flow part of the total stream-flow as a function of the net increase in water stored above the ground-surface. In Publication 400 these quantities have been designated by the symbol r_f, and for the purposes of this note the corresponding quantities estimated by Sherman's method have been designated by the symbol r_f'.

(12) It would make this note unduly long to discuss in detail the elements of the two methods of estimating these quantities, both of which are covered in the references cited. Suffice it to say that among other quantities, that must be evaluated daily to compute r_f, are the additions to storage due to melting snows and the subtraction therefrom by evaporation. Sherman's unit-graph is inapplicable to streams affected by melting snows because he presents no way of evaluating the effect of this element. Furthermore, regardless of season, the chief defect in his method of evaluating the values of r_f' lies in his use of the age-old, crude device of expressing evaporation- and transpiration-losses purely as a function of rainfall and calling this function a constant for any calendar month when, as a matter of fact, we know that the evaporation-losses vary considerably from day to day, and that greater variations of it are caused by weather-elements other than rainfall.

(13) *The question of priority* of use of the basic principles involved in the surface-runoff equations and/or curves may be difficult, and perhaps relatively unimportant, to establish. Nevertheless, it may be said that use of these principles can be traced back to 1911 in the computations on which Publication 400--which appeared in 1929--is based, and that these are stored in the library of the Museum of Science and Industry where they are available for inspection by any responsible interested person.

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Chicago, Illinois

APPENDIX B--A REVIEW OF "A NEW METHOD OF ESTIMATING STREAM-FLOW" BY J. A. FOLSE

Merrill Bernard

It is with difficulty that this reviewer has arrived at what is felt to be a fair evaluation of "A new method of estimating stream-flow" by J. A. Folse, Research Associate, Carnegie Institution of Washington, published in 1929. This work, together with the development of an evaporation-formula, comprises Bulletin 400 of the Carnegie Institution and presents the work of the late Dr. John F. Hayford. Mr. Folse, Dr. Hayford's principal assistant, later concluded the work and arranged its publication. Some idea of the magnitude of the project can be derived from the statement of Mr. Folse that Dr. Hayford himself spent some 2000 hours on the non-routine parts, and over 32,000 man-hours by 41 persons were consumed in making the study.

The apparent lack of appreciation for, and practical utilization of, this work on the part of hydrologists and engineers can be understood. One having an appreciation of the intricacies through which fallen rain must pass to become a part of stream-flow will accept Dr. Hayford's array of variables and the periods throughout which they combine to make up stream-flow as being altogether possible and, with reservations, reasonable. Too, the lengthy equations and rather complicated mechanics of the method would be wholly justified if the stream-hydrograph, as computed from available antecedent data, compared reasonably with the observed flow. The reader is first attracted to the graphs supplementing the paper in which computed and observed flow are compared, to find a disappointing lack of agreement. He is to be forgiven for a skepticism which must color his impressions as he progresses through the report itself.

Questions are continually arising to which the reader finds no satisfactory answers in the text. Why, for instance, was a method, evolved from an experience in studying fluctuations in the levels of the Great Lakes, applied to a stream-flow problem at the other extreme of all conditions? The Wagon Wheel Gap watersheds are only a few hundred acres in extent, at an elevation of about 10,000 feet, comprising excessively steep slopes and producing stream-flow derived principally from melting snow. In the writer's opinion, Mr. Folse, in advocating the general use of the method, should have demonstrated its application to more normal watersheds.

The reader is in constant difficulty in attempting to discriminate between assumption and fact. Statements which the author may have intended to refer to his specific problem are in general terms and many of them, as statements of fact, are wholly unsupported.

On page 198 Mr. Folse asks the question: "The comparison of computed stream-flow with observed stream-flow will be given in such form as to help the reader to reach his own conclusions on certain pertinent questions. Are the formulas with the constants in them mere interpolation-formulas which reproduce fairly well the observed daily discharges of the period used in computing the constants, or, on the other hand, do these formulas represent the facts of nature and are the derived constants real physical constants such that for these streams they express the relations actually existing at all times between the meteorological facts and the discharge of the stream?"

Such factors as rainfall, temperature, and evaporation, entering into the determination of change in storage, r, have, of course, real physical significance. The constants, r'_1, r'_2, ... r'_{10} and r'_{f_1}, r'_{f_2}, ... $r'_{f_{10}}$ are understood to be the indirect measure of such watershed-characteristics as soil-type, cover, slope and shape, arrangement of stream-system, and geological structure. As they have been developed, these factors are wholly empirical and may or may not justify the designation, real physical constants. Such a decision must await the time when their values can be checked by deduction from elementary principles.

In the light of the title of the paper a distinction should be drawn between runoff and stream-flow. There is a difference between these terms, although both are measured in the same physical units, such as cubic feet per second, and both are functions of time. Runoff implies contributions from all units of area and on small watersheds can reasonably be expressed as average depth whether it be surface-runoff or underground. By discharge is meant the volume of water flowing in the stream draining the drainage-area (at the cross-section where the stream leaves the drainage-area) per unit of time, regardless of whether or not part of the flow may have been underground. Its expression as average depth over the watershed has no dimensional significance and should be considered as an abstract term, reflecting the magnitude of the flow in terms of the area of the watershed. In a very small drainage-area, such as the Wagon Wheel Gap drainage-areas, the difference between these quantities at any instant of time is negligible, but for larger areas the difference becomes increasingly great.

The question of similarity between Mr. Folse's method and the unit-hydrograph method presented by L. K. Sherman (Eng. News-Rec., April 7, 1932) has been raised. Perhaps all methods as they approach and parallel Nature's processes, tend to take the same form. The methods are alike in several respects. The Folse Method separates rainfall, or melting snow, occurring in any day into evaporation and change in storage and distributes such change in storage throughout a period of 257 days following the date of such rainfall, the amount of the increment being fixed by a constant, r, which presumably is a measure of the physical characteristics of the particular watershed. The unit-hydrograph method distributes the daily (or other time-unit) contributions of surface-runoff to stream-flow throughout a period following the rainfall, equal to the time-base of an observed hydrograph which has resulted from a rainfall confined to the time-unit. The amount of the increment of stream-flow is found to be proportional to the daily (or other time-unit) ordinates of the unit-hydrograph. The shape of the unit-hydrograph for relatively small areas with steep slopes is characterized by short time-base and high maximum ordinate, while unit-hydrographs of longer time-base and smaller maximum ordinate become the measure of physical characteristics of large watersheds with flatter slopes.

There are no basic data to be found in the paper on stream-flow which would lend themselves to the procedure of the unit-hydrograph method. Rainfall-depth recorded at 24-hour intervals cannot be utilized for small watersheds having short concentration-periods, as the Wagon Wheel Gap areas. However, in the paper "A new evaporation-formula", also appearing in Publication 400, is to be found, on page 108, a listing of factors offering the opportunity to compare results obtained through application of the two methods. Consider the net change in storage to be observed rainfall on land, I, minus estimated evaporation from land-surface, E_1. Consider the region's distribution-graph as having daily values proportional to r (page 105) and representing

Table 1--Comparison of results obtained by the two methods

(Unit = 0.001 foot of depth on lake-area)

Date	Obs'd rainfall I	Est. E_1	Change storage $(I - E_1)$	Distribution graph	Computed distribution on day and days succeeding April						
					2	3	4	5	6	7[b]	9
1911				o/o							
Apr. 2	2	+ 1	+ 1	1.0	.010						
3	2	+ 4	- 2	7.0	.070	-.020					
4	17	+ 3	+ 14	17.0	.170	-.140	.140				
5	40	+ 3	+ 37	4.0	.040	-.340	.980	.370			
6	43	+ 4	+ 39	4.0	.040	-.080	2.380	2.590	.390		
7	20	+ 1	+ 19	.5	.005	-.080	.560	6.290	2.730	.190	
8	1	+ 1	0	.5	.005	-.010	.560	1.480	6.630	1.330	
9	0	- 1	+ 1	.5	.005	-.010	.070	1.480	1.562	3.230	.010
10	0	+ 1	- 1	.5	.005	-.010	.070	.185	1.562	.760	.070
11	0	+ 5	- 5	.3	.003	-.010	.070	.185	.195	.760	.170
12	11	+ 4	+ 7	.3	.003	-.006	.070	.185	.195	.095	.040
13	27	+ 5	+ 22	.3	.003	-.006	.042	.185	.195	.095	.040
14	40	+ 15	+ 25	.3	.003	-.006	.042	.111	.195	.095	.005
15	26	+ 15	+ 11	.3	.003	-.006	.042	.111	.117	.095	.005
16	2	+ 13	- 11	.3	.003	-.006	.042	.111	.117	.057	.005
17	0	0	0	.3	.003	-.006	.042	.111	.117	.057	.005
18	1	+ 8	- 7	.3	.003	-.006	.042	.111	.117	.057	.003
19	18	0	+ 18			-.006	.042	.111	.117	.057	.003

Computed distribution on day and days succeeding April									Daily var'n run-off I_v	Tot. run-off $(I_v + 6)$	Est. run-off[a]	Date
10	11	12	13	14	15	16[b]	18	19				
												1911
									0	6	6	Apr. 2
									0	6	6	3
									0	6	4	4
									1	7	6	5
									5	11	9	6
									10	16	13	7
									10	16	14	8
									6	12	18	9
-.010									3	8	7	10
-.070	-.50								1	7	4	11
-.170	-.350	.070							0	6	4	12
-.040	-.850	.490	.220						0	6	4	13
-.040	-.200	1.182	1.540	.250					3	9	7	14
-.005	-.200	0.280	3.740	1.750	.110				6	12	10	15
-.005	-.025	0.280	.880	4.250	.770	- .110			7	13	10	16
-.005	-.025	.035	:880	1.000	1.870	- .770			5	11	8	17
-.005	-.025	.035	.110	1.000	.440	-1.870	-.070		3	10	4	18
-.003	-.025	.035	.110	.125	.440	- .440	-.490	.180	1	7	4	19

[a] Column 12, Table 37, p. 108, Publication 400, Carnegie Institution of Washington.

[b] $(I - E_1) = 0$ for April 8 and April 17 and computed distributions for these days .000 throughout.

the percentages of $(I - E_1)$ delivered to the lake on any day throughout the 16 days following a particular rainfall. This accounts for 37 per cent of rainfall less evaporation, the remaining 63 per cent being accounted for in the negligible daily increments beyond the 16th day following the rainfall and that portion lost to runoff as seepage into deep ground-water storage. Apply this distribution-graph to the daily values of $(I - E_1)$, distributing each day vertically throughout the period in which that day's rainfall contributes to runoff, and accumulate the daily increments horizontally to give estimated runoff on each day throughout the period. Add these daily values to I_c, the constant part of runoff, obtaining total estimated runoff comparable to that shown in column 12 of Table 37. The computations are shown in Table 1.

The foregoing criticism, the writer hopes, will be accepted as constructive for he feels it could not have been avoided in any worth-while review of the work. The writer believes the author's objective of a practical method of stream-flow determination, based on observed meteorological facts, has not been attained. The study, however, is admirable in its courageous attempt to deal with all of the factors. Dr. Hayford and Mr. Folse have not, as have all others presenting similar methods, found it necessary to caution the reader that the method applies to only such seasons as involve no melting snow and ice.

The intrinsic value of this work will increase, as time passes, as the log of a journey into fields yet to be explored.

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APPENDIX C--THE HORTON METHOD FOR DETERMINATION OF INFILTRATION-RATES

L. K. Sherman

This paper gives data on certain observed rates of soil-infiltration and other rainfall-losses during the progress of a storm. Infiltration takes place only during the period of rainfall and surface-runoff (excepting cases like the dry Western stream-beds). R. E. Horton (Surface-runoff phenomena, Bull. 101, Horton Hydrologic Laboratory, Edwards Brothers, Pub. Ann Arbor, Mich.) has presented a method whereby the hydrograph of surface-runoff may be derived from the observed stream-flow hydrograph. With this hydrograph of surface-runoff and with the application of M. M. Bernard's "pluviograph" (An approach to determine stream-flow, Trans. Amer. Soc. C. E., No. 100, 1935), it is possible to find the infiltration and other losses during the storm-period, on a drainage-basin, provided good records of rainfall and of stream-flow are available.

This derivation of infiltration or losses is best illustrated by an example. The reader is assumed to be familiar with the works of Horton and Bernard just referred to. The example, Figure 1, is identical, so far as rainfall and surface-runoff are concerned, with Figure 12 of Horton's Bulletin 101. The observations were for a rain of 1.28 inches, August 1, 1932, on a drainage-area of three square miles of Ralston Creek Basin in Iowa.

The four lines on Figure 1 are mass-lines or, diagrams, of rainfall, P, surface-runoff, Q_a, surface-detention, or rain-water, on the ground at a given time, d_a (Horton's symbol is δ_a) and losses including infiltration, F. All of Figure 1 is the same as Horton's Figure 12 excepting the two heavy lines d_a and F which replace the similar dotted lines of Horton. Given the mass-lines P, Q_a, and d_a, the value of F is found for any time-period by the storage-equation

$$\text{Inflow} = (\text{outflow} \pm \text{storage})$$
$$P = Q_a + F + d_a$$

P is known from the observed rainfall; Q_a is derived by Horton's method.

The derivation of d_a by the writer requires further explanation. The procedure was as follows: (a) From Horton's surface-runoff hydrograph derive the pluviograph of 100 per cent runoff, q_p (see Bernard's paper); in this example q_p, at time 8:30, = 190 cfs. (b) At any given time, say 8:30, find the difference between mass-precipitation P and mass 100 per cent surface-runoff; with both units in inches depth over the drainage-area, this gives the value d_p or surface-detention depth at 8:30, namely, P (= 1.28 inches) less 100 per cent mass-runoff Q_p (= 0.049 inch) gives d_p = 1.23 inches. (c) By Manning's Formula, and assuming that hydraulic radius equals depth, for wide shallow streams, we know that q varies as d to the 5/3 power. The same is also apparent from Horton's surface-runoff formula on page 20 in reference above. (d) Now compute d_a, the actual depth of water (surface-detention) at 8:30, namely: $(q_a/q_p) = (d_a/d_p)$, wherein both values of d are raised to the 5/3 power. From the foregoing $d_a = 1.070$. The value of q_a is 150 cfs as per Bulletin 101 (Table 6, col 6). The ratio (q_a/q_p) is 0.79. It is a constant for all simple hydrographs like this one.

Now plat the derived ordinate d_a at 8:30. In a similar manner plat d_a-points for other times to give the complete graph of surface-detention.

We are now ready to apply the aforesaid storage-equation. The value of initial loss plus infiltration at 8:30 is $(d_o + F) = 0.172$ inch. In a similar manner other points on the mass-line of losses may be found.

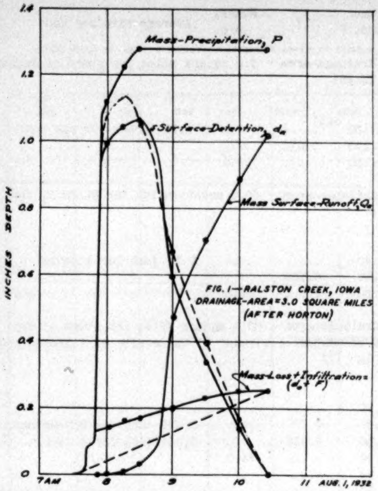

FIG. 1—RALSTON CREEK, IOWA
DRAINAGE-AREA = 3.0 SQUARE MILES
(AFTER HORTON)

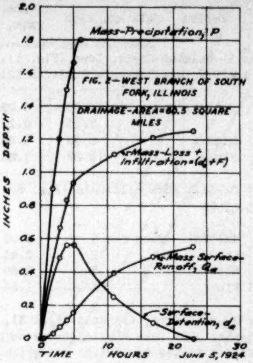

FIG. 2—WEST BRANCH OF SOUTH FORK, ILLINOIS
DRAINAGE-AREA = 80.5 SQUARE MILES

The duration of surface-runoff may be segregated into three periods in so far as infiltration and losses are concerned. During the initial period--beginning of rain up to the time when surface-runoff starts--all of the rain is used up in wetting the surface and the vegetation and in filling up small pockets as well as some infiltration-loss. This water is initial detention, d_o, and is a volume. The volume d_o will depend upon antecedent moisture-conditions of the soil. The duration of the initial period depends upon the intensity of the rainfall.

During the middle period--from beginning of surface-runoff until effective rain ceases--practically all the loss is due to infiltration, F, provided the rain-intensity equals or exceeds the infiltration-capacity. In this event, f, in inches depth per hour, is the infiltration-capacity (average) for the basin.

During the terminal period--from the end of effective rainfall to the time when surface-runoff ceases--the apparent value of f decreases. This is due to the fact that the surface-detention water, d_a, moving off the ground, is leaving smaller and smaller portions of the basin subject to infiltration.

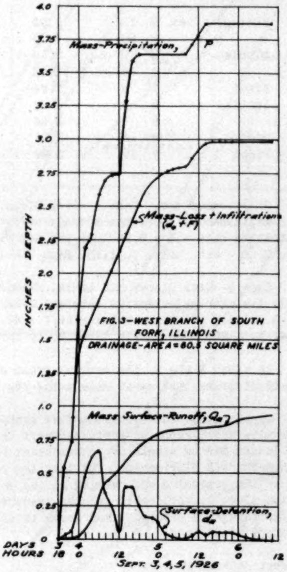

FIG. 3—WEST BRANCH OF SOUTH FORK, ILLINOIS
DRAINAGE-AREA = 80.5 SQUARE MILES

The middle period only is useful to determine a true value of the rate of infiltration-capacity, f.

The writer has derived the infiltration-capacity f, together with losses F for the initial and terminal periods, for observed rainfall on several basins. The results for cases 1, 2, and 3 are given on page 314.

Case 1--Ralston Creek, Iowa (Fig. 1), with drainage-area = 3.0 square miles for storm of August 1, 1932 (see Horton's Bulletin 101, pp. 35-38)

Period	Date and time	Acc. rain, P	Acc. loss, F	f	Runoff o/o	Average rain per hour
Initial	Aug. 1 7:30	0.00				
	7:50	0.13	0.130	.....	....	1.28 inches for one hour
Middle	8:30	1.28	0.172	0.072	....	
Final	10:25	1.28	0.250	.....	19.6	

Case 2--Salt Fork, Illinois (Fig. 2), with drainage-area = 60.5 square miles for storm of June 5, 1924

Period	Date and time	Acc. rain, P	Acc. loss, F	f	Runoff o/o	Average rain per hour
Initial	June 5 0	0.00				
	1	0.40	0.40	.....	....	0.30 inch for 6 hours
Middle	6	1.80	1.00	0.160	....	
Final	23	1.80	1.25	.....	69.5	

Case 3--Salt Fork, Illinois (Fig. 3), with drainage-area = 60.5 square miles for storm of September 1931 (see "Drainage-investigations in central Illinois" by University of Illinois and United States Department of Agriculture Fig. 17)

Period	Date and time	Acc. rain, P	Acc. loss, F	f	Runoff o/o	Average rain per hour
Initial	Sep. 3 18	0.00				
	3 20	0.90	0.90	.....	....	
Middle	4 2	2.19	1.60	0.12	....	0.272 inch for 8 hours
	4 18	3.62	2.50	0.056	....	0.241 inch for 6 hours
Final	5 8	3.64	2.80	.....	76.8	
Initial	5 8	3.64	2.80	.....	....	
	5 8	3.64	2.80	.....	....	
Middle	5 14	3.87	2.99	0.03+	....	0.03+ for 6 hours
Final	6 10	3.87	3.00	.....	(87)	
				Total	77.5	

Other cases are: Case 4--City Block, St. Louis, Missouri, drainage-area = 2.25 acres, for rain September 8, 1926, the average effective rate was 2.05 inches per hour for 46 minutes; infiltration-rate = f = 0.55 inch per hour; total runoff = 68 per cent rainfall. (See Proc. Amer. Soc. C. E., Oct. 1934, p. 1135, Figs. 15-16, area A, by Horner and Flynt.)

Case 5--City Block, St. Louis, Missouri, drainage-area = 3.27 acres, for rain August 27, 1921, the average effective rate was 2.32 inches per hour for 45 minutes; infiltration-rate = f = 0.98 inch per hour; total runoff = 47 per cent rainfall. (See Proc. Amer. Soc. C.E., Oct. 1934, p. 1135, Figs. 15-16, area B, by Horner and Flynt.)

In cases 4 and 5, the mass-diagrams of Horner and Flynt have been considered as surface-runoff diagrams, the sewer only being regarded as having channel-flow.

Conclusions--The foregoing five examples indicate: (1) That Horton's method may be used to determine hydrographs of surface-runoff from observed channel-flow; (2) that infiltration-rates and losses during single or intermittent rainfalls can be derived by Horton's method combined with Bernard's pluviograph; (3) that the rate of losses, during a surface-runoff period, is greatest at the beginning and nothing at the end of the surface-runoff period; (4) that the middle period alone is applicable for the measurement of infiltration-rates; (5) that further studies by the foregoing procedure may serve to establish the relation of losses to antecedent soil-moisture conditions.

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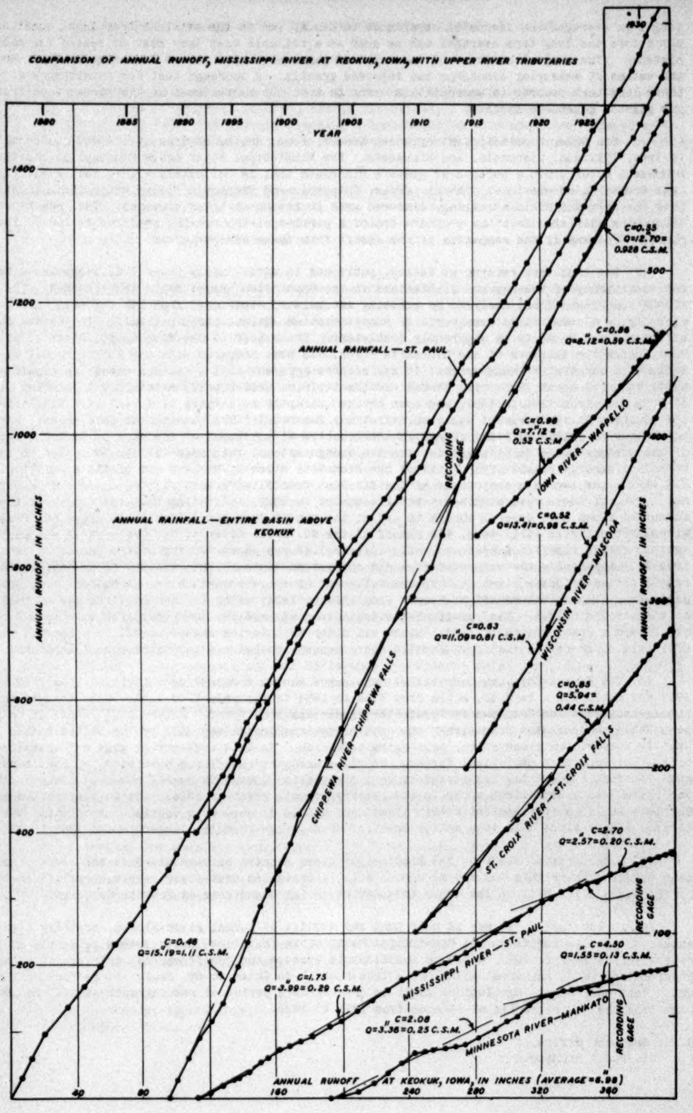
APPENDIX D--CONSISTENCY TESTS OF LONG-TERM RUNOFF-RECORDS IN THE UPPER MISSISSIPPI RIVER BASIN SUGGESTED BY STUDY OF WATER-SUPPLY PAPER 772 OF UNITED STATES GEOLOGICAL SURVEY

Walter J. Parsons

(1) In the development of the 9-foot slack-water navigation works on the Upper Mississippi River, the relation of river stages and discharges during particular periods of years to the



COMPARISON OF ANNUAL RUNOFF, MISSISSIPPI RIVER AT KEOKUK, IOWA, WITH UPPER RIVER TRIBUTARIES long-term averages has become of importance in design and in the settlement of legal questions. But before the long-term averages can be used as a reliable base they must be tested for consistency. The exact locations and the types of gages used have varied from time to time, and the method of measuring discharge has improved greatly. A thorough test for consistency of these long-term records is essential in order to test the correctness of the conversions from one gage or method to another.

(2) The Upper Mississippi River above Keokuk, Iowa, drains an area of 119,000 square miles in Iowa, Illinois, Wisconsin, and Minnesota. The Mississippi River above Minneapolis and the Minnesota River drain a portion of western Minnesota that is definitely within the level, treeless Great Plains province. The St. Croix, Chippewa, and Wisconsin rivers enter the main stem from the east and drain a rolling, timbered area in the Great Lakes province. The Iowa River enters the main stem from the west and drains a portion of the rolling prairies of Iowa. The runoff at Keokuk is the composite of the runoff from these diverse areas.

(3) The long-term records at Keokuk, published in Water-Supply Paper 772, suggested a test for consistency of the key runoff-stations in the Upper Mississippi Basin above Keokuk. The Keokuk runoff was first analyzed by plotting accumulated departures from its own mean, and secondly by a comparative mass-curve of runoff plotted against basin-rainfall. The Keokuk runoff-record was found to be apparently consistent. The runoff of the Mississippi River at St. Paul, below the entrance of the Minnesota River, was next compared with the Keokuk runoff by means of a comparative mass-curve. It was at once apparent that a decided change in runoff-habit occurred about 1922. The Keokuk and the St. Paul unit-runoffs maintained a constant ratio of 1 to 0.57 from 1891 to 1922, and then changed abruptly to a ratio of 1 to 0.37. Since 1922 the recorded St. Paul runoff has been definitely subnormal. The question at once arose: Why the change in 1922? No vital change in the location or equipment of the gage or in the method of measurement could be discovered. Was the change a local phenomenon or did it appear in the runoff of other streams? The runoff of the Minnesota River at Mankato and of the Mississippi at Elk River, the two main components of the St. Paul runoff, were next plotted against Keokuk runoff. Both of these rivers showed a break downward in 1922, indicating that the causes of the subnormal flows were general enough to affect the runoff from the entire basin above St. Paul. Widening the circle still more, the runoff of the St. Croix River at St. Croix Falls was plotted against Keokuk runoff. A constant ratio of 1 to 1.18 was shown for the entire period of record, 1909-34. Apparently the subnormal area did not extend eastward into the St. Croix Basin. The runoff of the Chippewa River at Chippewa Falls and of the Wisconsin River at Muscoda also showed constant ratios to the runoff at Keokuk from 1914 to 1934, which further confirms the normality of the Wisconsin area. The runoff of the Iowa River at Wapello, Iowa, compared with Keokuk runoff showed a break upward in 1922. Since all other tributaries showed normal or subnormal runoff, this super-normal runoff at Wapello was necessary to balance the total runoff at Keokuk.

(4) The Keokuk-Chippewa comparative mass-curve showed a marked peculiarity. From 1888 to 1914 the ratio was 1 to 2.18, while from 1914 to 1934 it was only 1 to 1.82. What changed the runoff-habits of the Chippewa in 1914? The answer was soon found. Before 1914 runoff at Chippewa Falls was computed from either one or two gage-readings a day made by the United States Weather Bureau, power-companies, or logging companies. In 1914 a recording gage was installed by the United States Geological Survey, and since then the runoff has been based on continuous gage-records. Apparently the marked diurnal fluctuation caused by nearby power-plants and mills had introduced a consistent error in the recorded runoff prior to 1914. The 46-year record at Chippewa Falls is inconsistent within itself and should be used with caution. Apparently the 20-year record since 1914 is a better index of normal flow than the longer period 1888 to 1934.

(5) A comparative study of the Mississippi gages located between St. Paul and Keokuk, using mean annual gage-heights instead of annual runoff, indicated that river-levels were influenced by the subnormal runoff of the upper tributaries as far downstream as Prairie du Chien.

(6) In conclusion, it may be said that any studies of normal river-slopes, ordinary high-water, or average runoff on the Mississippi River above Prairie du Chien, based primarily on the recent period 1922 to 1935, would be questionable because the runoff was not only subnormal but progressively more subnormal going north from Prairie du Chien to St. Paul. It is further indicated that more normal conclusions might be drawn from a period of records such as 1891 to 1921 than from the entire period of records from 1891 to 1935.

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APPENDIX E--COMMENTS ON DATA OF INTENSITY AND FREQUENCY OF RAINFALL

Merrill Bernard

Prompted by the suggestion in the Chairman's memorandum to Committee members in which the question of revision of the Yarnell rainfall-charts was raised, I conferred recently with D. L. Yarnell and Adolph Meyer with the view of reaching a conclusion on this and other related questions. A proposed project grew out of this conference which we should like to have the Committee consider and advise upon.

It is believed that we can expect from now on a more accurate and dependable record of rainfall and other observed meteorological data than heretofore collected. This very increase in accuracy and dependability makes it necessary for us, as nearly as possible, to approach the limit of usefulness of all past data if we are to successfully correlate the future with the past.

It should be stated that to those who know the circumstances under which past records have been gathered there can be no real criticism of the agencies which have brought down to us the records covering an era throughout which there was shown little appreciation for the scientific attitude toward the gathering and analysis of weather-data.

There have been todate the following general studies of recorded precipitation. (1) Rainfall-equations for durations to 120 minutes, by Adolph F. Meyer, presented in his "Elements of hydrology." (2) Isopluvial charts for durations of one to six days, prepared by the engineering staff of the Miami Conservancy District and published as "Technical report, Part V." These studies were made about 1917. (3) The writer, in 1932, combined these studies and presented in the form of charts factor-values for use in a general equation for rainfall-rate, applicable to durations longer than 120 minutes. (4) In 1935 David L. Yarnell, Senior Drainage Engineer, Department of Agriculture, published Bulletin 204, entitled "Rainfall intensity-frequency data." This work presented rainfall-depths for durations of five minutes to 24 hours in the form of isohytel charts.

These studies utilized in varying degree the same basic data which were, to a large extent, those published by the United States Weather Bureau. Where the range of time and frequency overlap, rainfall-depth or average rate produced by each of the methods are comparable for many localities and consistently so for certain frequencies. There are, on the other hand, many cases of marked disagreement in the results produced by the four methods.

The studies referred to above have one characteristic in common in that all were limited by both time and money. This accounts for the difference in criteria which makes direct comparison of the studies impossible and becomes a principal criticism of the work so far done.

Popular use of these works bear witness of their value to the engineering profession and will warrant from time to time revisions and refinement. It is expected that other investigators may make similar use of the basic data. Such a picture has suggested a project which proposes to bring to date and to compile in acceptable form all precipitation-data from all available sources. Such an undertaking would be comparable to projects considered by the National Water-Resources Committee dealing with floods and would have equal if not greater usefulness. Suggested phases of such a study incidental to the gathering and listing of data are: (1) The relation between number of stations and area served per station; (2) a critical analysis of the station-year method of determining the rainfall-depth versus frequency relationship; (3) the proper definition of the limits of areas having like precipitation producing characteristics within which station-records may justifiably be grouped; and (4) the development of a method of detecting irregularities within a record and a practical means of determining and applying a corrective factor.

Should the Committee feel the proposed project feasible and decide to sponsor or encourage it, advice on method and cost will be appreciated.

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REPORT OF THE COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1935-36

(Physical properties of soils as affected by the degree of cation saturation)

F. J. Veihmeyer, Chairman

From among the suggestions made by members of the Committee for the subject of this annual report, that submitted by E. A. Willis was selected. The Committee has summarized the opinions of competent investigators concerning the changes in the physical properties of soils produced by changes in the degree of cation-saturation both from an agricultural and an engineering viewpoint.

The literature on base-exchange phenomena is voluminous. It was decided, therefore, to make no attempt to digest published material but rather to obtain data and opinions from investigators who are doing current research in this field. This report in effect is a symposium on this subject.

The whole question of cation-exchange, of course, can not be considered. The Committee restricted its inquiry to the following questions:

(1) What are the best methods of expressing (a) the total cation-exchange capacity and (b) the amounts of replaceable cations of various kinds?
(2) Have you made laboratory measurements of changes in physical properties of soils produced by changes in the kinds and proportions of replaceable cations present in the absorptive complex which would indicate that similar changes under field-conditions are of practical importance?
(3) By changing the kinds and proportions of replaceable cations in the absorptive complex in soil in place in the field, have you been able to make measurable changes in physical properties of the soil?
(4) Have you made any measurements on changes in the properties of soil as an engineering material which you regard as resulting from changes in the kinds and proportions of replaceable cations in the absorptive complex of the soil?

The first question was prompted by the confusion of terms which have appeared in the literature, such as degree of saturation, degree of unsaturation, per cent of cation-saturation. In some cases the amount of a particular exchangeable cation is expressed simply as milligram-equivalents per 100 grams of soil with no information as to what proportion of the total exchange capacity of the soil for the ions is satisfied. The situation is similar to that when the moisture-content of the soil is expressed as the ratio of water to soil without reference to the amount the soil is capable of holding under specified conditions. The methods used to determine the total cation-exchange capacity or the amounts of replaceable cations present and the accuracy of them are not considered in this report.

The answers to the first question were unanimously in favor of expressing total cation-exchange capacity in milligram-equivalents in a given weight of soil. Most investigators preferred milligram-equivalents per 100 grams of soil. Many preferred to express the amounts of a particular replaceable cation present in the exchange-complex as a ratio to the total cation-exchange capacity. The replies to question (1) are therefore not listed.

M. S. Anderson and coworkers (United States Department of Agriculture, Bureau of Chemistry and Soils) have studied [see 1, 2, 24 under "References" at end of report] various properties of a group of soil-colloids saturated with single cations and found that colloids of high silica-sesquioxide ratio are much more influenced by kind of cation present than is a colloid with a low silica-sesquioxide ratio. The moisture-equivalent of the colloid of a pedocal soil saturated with sodium is about double that of the same colloid saturated with calcium. A red lateritic soil-colloid has small base-holding capacity and has about the same moisture-equivalent, regardless of the cation present.

L. D. Baver (University of Missouri) studied [3] soils that were saturated with various ions and observed only the sodium-ion had a marked effect upon most of the physical properties studied, with the exception of heat of wetting, hygroscopicity, dispersion, and slaking. In the latter determinations the potassium-ion simulated the sodium-ion. Actually, it lowered hygroscopicity and heat of wetting to a greater degree than the sodium-ion. It occupied an intermediate position between the divalent ions and the sodium-ion in the rate of slaking and flocculation tests. The outstanding results appeared to be the similarities existing between hydrogen and calcium-ion.

He also investigatec the effects of exchangeable ions on the properties of colloidal clay [4]. The same tendencies were observed here. There was little difference between the hydrogen-saturated and the calcium-saturated systems. His studies show that when calcium was in excess stable flocculation was produced and also that 25 per cent saturation with sodium-ion was sufficient to bring about dispersive and other effects of this ion. He feels that this point should be quite important when comparing sodium- and calcium-ion effects in soils.

Other studies [5], investigating adsorbed and combined water in soil colloids, showed that sodium- and potassium-systems adsorbed the least amounts of water and that hydrogen adsorbed the most. The result suggests that the adsorbed water was related to the volume of the adsorbed ion.

Further investigations on the effect of adsorbed ions on the swelling of colloidal clays [6, 17, 26] showed that the potassium-saturated systems swelled the least and that calcium and hydrogen clays were similar in their behavior with the calcium clay swelling slightly more than the hydrogen. Permeability studies [17] showed that the monovalent ions produced membranes having the slowest permeability. Hydrogen-saturated systems were always more permeable than calcium-saturated.

Baver found in recent investigations [7, 8] that the effect of the calcium-ion on the formation of stable secondary particles was largely indirect through its influence on the organic matter. No significant correlation was found between granulation and the amount of exchangeable calcium present. This statement was made for hydrogen and calcium soils only and does not apply to those soils containing sufficient quantities of exchangeable sodium to be deleterious to the physical properties of soils. He found that on humid soils where leaching removed most of the sodium applied as fertilizer strong indications existed that changes in the physical properties of soils by the addition of soil-amendments will be slight except as those amendments contribute to the formation and stability of organic colloids. Baver refers to Winterkorn's work [25, 27, 28] in which these results are being used in a practical way in the stabilization of low-cost roads.

G. B. Bodman (University of California) has made measurements of the effect of replacement by calcium, sodium, and hydrogen of existing replaceable cations in a few soils of strikingly different characters. Volume-measurements were made during drying from the two-phase (water-saturated state) soil at the "sticky point" through various humidities down to oven-dryness at 105° C.

Replacement by sodium caused increases both in initial and in final apparent density in all cases by amounts ranging from one to five per cent over that of the untreated soils. The effect was definite but not great. Calcium and hydrogen replacement, on the other hand, were sometimes practically without effect and sometimes caused decreases of from three to four per cent in the final apparent density below that of the untreated soils. There is some indication that the magnitude of the effect is associated with the chemical composition (other than its replaceable cations) of the clay present in the soil.

The effectiveness of the sodium-ion in producing and maintaining a high degree of dispersion in water suspensions of soil-clays has been repeatedly observed by him. Calcium soils gave a much lower degree of dispersion than sodium soils. Ammonium soils were also less highly dispersed than sodium soils. He has made no quantitative measurements but his qualitative results indicate a very great decrease in permeability resulting from sodium replacement and an increase from calcium and aluminum.

Bodman found that with heavy clays in which sodium, calcium, and aluminum have replaced other cations and have been puddled, and then repeatedly frozen and thawed before making qualitative observations on the hardness of the aggregates so produced, the sodium hardened while the calcium and aluminum softened the crumbs. He believes that similar alterations in the replaceable cation status of such soils in the field would have similar effect. He also feels that the effect of sodium and calcium on the permeability appears of greatest practical significance, the adverse sodium effect being more marked than the beneficial calcium effect.

The practical significance of the effects of calcium- and sodium-ions on the density appears to be less important. The physical condition, however, of the sodium soil, because of the high degree of dispersion associated with a high ratio of replaceable sodium to total replaceable cations makes it susceptible to the production of what is usually regarded as an undesirable agricultural condition. Sodium soils, in short, have behaved as though much more clayey, and may be expected to be generally less manageable.

The effect of the presence or absence in the liquid phase of electrolytes, and their nature and abundance is of very great significance. His observations on permeability, dispersion, and softness of aggregates point to the marked effect which removal of electrolytes has upon these characteristics in soils, the cation-status of which has been altered. He believes these effects are of field-significance.

Bodman points out that the physical properties of soils which are undesirable agriculturally may be desirable from the point of view of the construction engineer. For example, impermeability in an earth-fill dam is presumably desirable. Likewise, the production of high apparent density in adobe-brick may possibly be considered desirable, other things being unaltered thereby. He is of the opinion that soils rather highly unsaturated with bases may be rendered more permeable because of the change. Such a state is frequently associated with an advanced stage of weathering of the soil-profile. It is associated with an actual decomposition and more or less of a moving out of the clay complex, thus rendering the soil texturally coarser. This physical alteration of the soil is, however, a long-time affair.

C. W. Botkin (New Mexico College of Agriculture and Mechanic Arts) found [10] that flocculation is altered by additions of one-half per cent sodium chloride and one-half per cent aluminum sulfate. The compression-strength is greatest when the moisture is sufficient for maximum density. This critical amount is higher for loams containing sodium compounds, and appears to be less when the loams are deflocculated by leaching; but it is not increased by flocculation with aluminum sulfate. The compression-strength is decreased by the presence of sodium chloride and is increased by the removal of this salt or the carbonate with water, indicating that flocculation decreases the binding power of the colloids. Flocculation with aluminum sulfate, however, did not greatly influence the compression-strength.

He has found that high heads of water cause small increase in both penetration and percolation in the flocculated soils. In the deflocculated soils the higher heads, for a time, caused small decreases in the rate of water-movement. He interprets these phenomena to result from the swelling of the soil colloids which is greater for the deflocculated soils and more effective in retarding water-movement when the soils are more compact.

He found that the deflocculated soils contained larger amounts of replaceable sodium while the flocculated soils contained larger proportions of calcium and aluminum. Amounts of replaceable bases were not determined but the sodium-content was increased by treatments with a 0.5 per cent of sodium-chloride solution.

He has studied [9] the effect of different sodium compounds and other constituents of fertilizer and alkali on the movement of water through soils. Different correlations were obtained with increasing quantities of these constituents and the influence on water-movement which have a definite relation to the replaceable bases.

The penetration of water into the soils was retarded by sodium and potassium compounds (0.5 per cent) and by clay and silt (5 per cent). The sodium compounds caused a much greater depression of permeability than the other substances, the influence decreasing in the following order: Carbonate, acetate, chloride, nitrate, silicate, and sulfate. With varying proportions of carbonate, chloride, or nitrate of sodium, the depressing effect appeared to increase more rapidly than the concentration. In a general way permeability increased with the valence of the basic constituents of the compounds added to the soils. There was, however, a large difference in the permeability-influence of the different univalent metals and of the different compounds of any one metal. The chlorides were more depressing than the sulfates.

T. F. Buehrer and H. V. Smith (University of Arizona) have made percolation-studies on various soils that had been saturated with calcium sulfate, sodium chloride, and sodium carbonate, the last being used to observe the effect of high pH. Both the time required for the first drop to be delivered and the subsequent rate of percolation were measured. They show that the principal factor in the penetration and percolation of water is the pH of the percolating solution. When the soils were saturated with neutral sodium chloride they gave a percolation-rate as good or better than the check with distilled water, and as good or even better than when the soil was saturated with calcium. Apparently the rate of percolation is more a function of the dispersing effect of free hydroxyl-ions resulting from hydrolysis than the extent of saturation of the complex with either calcium or sodium. In all cases the rate was greatly decreased when sodium carbonate was used. They recognize, however, that when soluble salts are removed by percolating a sodium-saturated soil with water, the hydrolysis of the base-exchange complex would result in a dispersed condition of the soil which would reduce the percolation-rate. The above observation with the sodium-saturated soil is accounted for by the presence of sodium chloride in the percolating solution, which prevents this hydrolysis from proceeding to any appreciable extent. No measurements were made on the field percolation-rates, although numerous observations have been made which show that the soils which have a higher proportion of replaceable sodium over calcium are very much less permeable and have very slow percolation-rates.

They made measurements on the force required to break a column of soil one square inch in cross-section, that is, soil-tenacity. The soil-samples were saturated with calcium, using a one per cent calcium-sulfate solution, and with sodium, using one per cent sodium-carbonate solution. After preparation of the soil-columns, the samples were allowed to dry in the air, and were subsequently dried in the oven before measuring. The data show that saturating the soils with calcium greatly reduce their cohesiveness. The opposite was true when the soil was saturated with sodium in the presence of the hydrolytic alkalinity of sodium carbonate. The magnitude of the effect in the case of Pima Silty Clay Loam and Gila Loam was particularly striking.

They also made measurements on the modulus of rupture, which is also a measure of the cohesion of the soil, and is defined as the force required to break a briquette of known size and length. The solutions used for saturating the soils were five per cent sodium chloride, five per cent calcium sulfate, and one per cent sodium carbonate. The data show that without exception the cohesion of these soils is decreased by treatment with neutral sodium chloride, but increased considerably by treatment with sodium carbonate. The action of calcium sulfate is not constant. In some cases the modulus was increased, in others decreased.

They have also done some work on the relationship between the replaceable bases and the moisture-equivalent and saturation-percentage which show that the higher the amount of replaceable sodium, the greater the moisture-equivalent as well as the saturation-percentage. Buehrer points out that it is generally conceded that analogous properties such as the imbibitional water, decrease of swelling, and heat of wetting, are closely associated with the amount of replaceable sodium in the soil. He feels that a somewhat closer correlation can be obtained between the exchange-bases and these moisture-relations if one employs the calcium:sodium ratio as a basis.

They have done considerable work on the relation between the pH and exchangeable bases; and while they recognize this is essentially a chemical effect resulting from hydrolysis, its relation to the physical properties they feel is a very pertinent one. Results have been obtained from careful experiments with bentonites saturated partially with sodium and calcium, and they show that the pH remains substantially constant over a wide range of composition with respect to the replaceable bases, finally dropping off sharply to the pH value for calcium-saturated bentonite. They are making a correlation with data for actual soils of different types and remarkably close agreement is found between soils of a given region. Buehrer points out that differences may be expected for soils of humid versus arid regions, but in general better correlation seems to be possible for soils of the arid regions. A more rational basis for drawing an analogous curve for actual soils would be to sum up the replaceable divalent ions on the one hand, and the replaceable univalent ions on the other. When this is done he finds a somewhat better correlation. Doubtless, the greatest single factor in determining the physical condition of the soil is the free alkalinity resulting from the hydrolysis of carbonate and base-exchange complexes, and the dispersing effect of hydroxyl-ions on the soil colloids.

J. B. Cox (McBryde Sugar Company, Limited) reports the laboratory measurements made on samples of the core of the Alexander Dam [14] which were treated with sodium, calcium, and potassium hydroxide. The changes in the physical characteristics may be summarized as follows. No clear relationship between voids-ratio and pH is shown except an increase in voids-ratio in very light loads caused by a fluffy flocculation in the neighborhood of the iso-electric point. A clearly significant difference between bases is shown at higher values of pH, sodium producing the highest voids-ratio, potassium an intermediate, and calcium a markedly more dense and compact structure. No relationship is shown between the base concentration and compression but the coefficients of elastic expansion show a fairly consistent relation. For all bases the index of expansion is less (or the elastic expansion is greater) with high values of the pH. Permeability is influenced in the most marked and characteristic fashion as follows. The permeability at a given ratio is increased by slight additions of potassium and calcium hydroxide while sodium appears to decrease it. Increasing amounts of any base systematically reduce the permeability and the three bases approach the same curve until the point at which an excessive amount of calcium changes the texture of the soil and the permeability increases greatly.

He states there is nothing in this series of tests nor in his experience to indicate that similar changes are of common occurrence in the field. He treated a small quantity of material in a cut-off trench with soda-ash to render it impermeable with excellent results. This treatment was done in fluming the material to place and the soil was therefore not in place in the field.

F. M. Eaton (United States Department of Agriculture, Bureau of Plant Industry) feels that it is incomprehensible to speak of methods of expressing replaceable cations without specifying what method was used in making the determinations. He and V. P. Sokoloff [11] have shown that the amount of different cations found in the soil is dependent upon the method employed in the determination. He feels that if we regard solutions displaced from soils as representative of the soil-solutions then the significance of more dilute aqueous extracts become highly questionable. Only occasionally is it possible, he thinks, to convert the concentrations of constituents found in dilute aqueous extracts to concentrations as of the soil solution with reasonable accuracy. Exchangeable sodium as estimated on the basis of a 1:5 extract may be less than that on displaced solutions to the extent of 50 per cent or more.

He has carried out measurements on the moisture-equivalent of soils as affected by the character of the absorbed bases and finds that the moisture-equivalent of soils may be increased upward to 100 per cent by replacing the exchangeable bases with sodium-ion and removing the electrolyte by leaching with distilled water before centrifuging. When these soils were wetted with a tenth normal sodium or calcium electrolyte after saturating with sodium but before centrifuging, the effect of absorbed sodium-ion on the moisture-equivalent was very slight. This is in accord with results reported previously [23].

Eaton states that both in the field and in the laboratory sodium-ion in the exchange-complex impairs soil-permeability. Sodium soils are more permeable to saline irrigation-waters than to rain or non-saline irrigation-waters. Under field-conditions, soils are rarely, if ever, completely saturated with any one ion, calcium, magnesium, potassium, or sodium. The measurement of the proportions of the several exchangeable bases as of field-conditions requires a knowledge of the proportions of the bases in the soil-solution with which the soils were in equilibrium.

R. Gardner (Colorado State College) has shown that there is a decided change in settling velocities of particles as the ratio of sodium and calcium is changed in the replaceable base-complex indicating a difference in dispersion or hydration which might also be expected under field-conditions.

He has made a study of some of the physical properties of samples of soil taken from "slick spots" and from adjacent good soils which have decidedly different physical properties in the field. The laboratory studies indicate that the soils are very similar except for exchangeable bases and soluble salts, and that the difference in physical properties in the field are a result of these differences.

G. Gilboy (Massachusetts Institute of Technology) who with his coworkers has carried on extensive measurements on the physical properties of soil as an engineering material reports that he has made no tests as to the effect of exchangeable cations on these engineering properties.

J. H. Griffith (Iowa State College) has conducted comprehensive investigations [12, 13] on the physical properties of soils as an engineering material but reports that he has done practically nothing on the effect of replaceable cations.

F. E. Hance (Hawaiian Sugar Planters' Association Experiment Station) refers to experimental work which was conducted during the construction of Alexander Dam [14]. One treatment involved a large-scale operation of treating soil-bank material with solutions of sodium carbonate simultaneously with its delivery to the core of the dam. The objective was to bring about a high dispersion of colloidal soil material which, it was hoped, upon consolidation would form a very hard, compact, and impervious core. Other replacement-considerations included modifications of various slaking tests and taking note of the electrolytes, such as calcium nitrate, sodium chloride, etc., which may be present in the water used in the tests.

H. Jenny (University of Missouri) has made studies [15] on base-exchange, electrical potential, and stability (flocculation-values) of clays and says that the zeta potentials of Putnam clay particles depend on the charge and size of the adsorbed ion. For rare gas-type ions of equal size, the potential tends to be lower as the valency of the ion is higher. If the charge of the ion is kept constant, the potential is higher as the adsorbed cation (crystal lattice radii) is smaller. Colloidal particles with high potentials carry adsorbed ions which are easily exchangeable. The ease of replacement increases as the sixth power of the zeta potential. The flocculation-value of a given electrolyte increases parabolically with the zeta potential. For monovalent cations the flocculation-value is higher the smaller the size of the ion. The flocculating power of a cation is a positive exponential function of its ionic exchange-ability.

O. C. Magistad (Hawaii Agricultural Experiment Station) states that there is no work under way at his Station which bears upon questions 2, 3, and 4, but he refers to the work of Dr. F. E. Hance and J. B. Cox [14].

F. G. Merkle (Pennsylvania State College) points out that numerous experiments and observations show that the quantity and character of the individual cations in the colloidal complex have a controlling influence on the character of the colloid and hence its effect on the water-movement in the soil. In the vicinity of State College, Pennsylvania, the soils contain sufficiently highly oxidized iron so that their physical properties are to a large degree determined by this element. These plots show little differences in physical condition resulting from the use of different fertilizers and lime-compounds after 50 years, largely because their physical condition is so good as a result of this oxidized iron. In experiments with apple trees grown in metal rims where varying amounts of nitrate of soda were applied it was observed that the more nitrate of soda used, the more impermeable soil became; while on the field-plots nitrate of soda used for 50 years showed no effect on the physical condition. Sodium was found to be accumulating in the lower layer in the rims. The trees used so much of the moisture in the confined rims that none leached through and therefore sodium was allowed to accumulate. In the field, on the other hand, leaching effectively removed the sodium.

M. L. Nichols (United States Department of Agriculture, Soil Conservation Service) has measured the physical properties of soils involved in tillage and erosion and has used the Atterburg constants as indices of these properties. He is concerned principally with sheer value and frictional value and says that a number of investigators have shown that the Atterburg constants are affected by the kind and proportion of the replaceable cations.

P. G. Nutting (United States Geological Survey) has been working with bentonites and their absorbing power after activation by partial removal of bases by hydrogen substitution [18, 19, 20]. He points out that in the step by step leaching of the bentonites there is a rather abrupt change in physical properties and in adsorptive capacity when roughly two-thirds of the removable bases have been removed (hydrogen substituted). When less than that amount has been removed, a clay-mud will dry to a hard cake; when more than that has been removed (up to complete removal), the dried clay is incoherent. The adsorption-capacity of a bentonite clay is at a maximum when about one-third of its bases, chiefly iron and aluminum, remain in it. Beyond that removal, this adsorption-capacity decreases considerably and decreases most for weak cations. He finds that the action of very dilute acids on bentonites is marked by an anion-exchange while for strong acids it is a cation-exchange. Weak acids remove silica, strong acids chiefly bases from a bentonite. Partial removal of silica permits the conversion of bentonite to fuller's earth. He believes there is strong evidence that a similar effect is not uncommon under field-conditions.

L. B. Olmstead (United States Department of Agriculture, Bureau of Chemistry and Soils) has observed that addition of sodium-ions to a lateritic soil will affect its plasticity. The addition of three milli-equivalents of sodium hydroxide per 100 grams of soil, which gave a soil-reaction of pH 7, lowered the sticky point and the Atterburg "ausrollgrenze" of a sample from Texas. Another sample containing 34 per cent of clay was non-plastic. Upon addition of 3.6 milli-equivalents of sodium hydroxide per 100 grams of soil, the material became highly plastic clay. He determined physical constants on 52 profile-samples of 11 soils of the Erosion Experiment Station and found a significant negative correlation between the total exchangeable bases and the "ausrollgrenze", but not in the case of the other soil-constants, namely, minimum water of saturation [21] normal moisture-capacity, sticky point, water-vapor absorption at 99 per cent relative humidity, and the moisture-equivalent at 1000 gravity and 300,000 gravity. After eliminating the effect of texture, the residuals showed a significant negative correlation between the total exchangeable bases, or the base exchange-capacity, and both the sticky point and "ausrollgrenze". In the case of the other physical constants, the correlation was not significant.

W. L. Powers (Oregon State Agricultural College) tested briquettes made of alkali soil to which peaty organic matter had been added and found that their elasticity was increased and the briquettes were weakened.. He also found [16, 22] that permeability was greatly increased in the field in the alkali plots with the substitution of calcium for sodium. He measured the amount of substitution and found about 80 per cent in the first 20 inches.

R. E. Stephenson (Oregon State Agricultural College) and coworkers have noted improvement in penetration of irrigation-water, drainage, and aeration on black alkali land as calcium was gradually substituted for sodium in the exchange-complex. These are merely observations and the only data they have for their substantiation is the chemical data indicating a change from the sodium to the calcium complex. He regards the neutral complex in which calcium is the dominant cation as having more favorable physical properties for cropping purposes than the complex which is made acid by hydrogen, or alkaline by sodium. The sodium complex has most undesirable physical properties, resulting in a soil that is dispersed, poorly drained, and poorly aerated. The hydrogen complex as he has observed it does not result in soil of notoriously bad physical properties, but it is not as favorable as the calcium complex.

R. P. Thomas (University of Maryland) has observed that saturating the soil with different cations has affected considerably the rate of percolation of solutions through the soils. The alkali-bases, particularly sodium, decreased the rate of percolation and the alkali-earths increased it. He finds the ammonium cation seems to be somewhere between these two groups.

S. C. Vandecaveye (State College of Washington) has made laboratory measurements of changes in physical properties of soils produced by changes in the kinds and proportions of replaceable cations present in the absorptive complex. He reports that the results from field-experiments conducted over a number of years indicate that similar changes occur under field-conditions and that certain of these changes are of great practical importance. He has been able to bring about measurable changes in the physical properties of the soil by changing the kinds and proportions of the replaceable cations in the absorptive complex of the soil under field-conditions.

F. J. Veihmeyer and A. H. Hendrickson (University of California) report the effect of addition of various amounts of fertilizers on the moisture-equivalent and permanent wilting-percentage of five soils. Sodium nitrate, ammonium sulphate, calcium nitrate, urea, potassium sulphate, and treble super phosphate were used. The series for each soil contained concentrations of 100, 500, 1500, 2500, and 3500 parts per million of nitrogen, potassium, and phosphorous based on the oven-dry weight of the soil. The fertilizers were ground to a fine powder and mixed with the dry soil. The total cation-exchange capacity or amounts of replaceable cations present were not determined. The moisture-equivalents of the treated and untreated soils were not markedly different. In general, the permanent wilting-percentages were slightly higher for the treated soils than for the untreated soils. The soils treated with nitrogen fertilizers showed considerable increase in the permanent wilting-percentage when concentrations near the toxic limits for these salts were reached.

H. N. Watenpaugh (New Mexico State College of Agriculture and Mechanic Arts) states that he was able to change the hygroscopic content of a clay-soil by replacing all the bases with sodium or calcium. Such drastic changes in the soil would, he thinks, also affect the physical properties of these soils in the test-tube.

E. A. Willis (United States Department of Agriculture, Bureau of Public Roads) reports that samples of homo-ionic soils are being prepared at the University of Missouri as part of a cooperative project and the samples are being tested at Arlington for the determination of liquid-limit, plasticity-index, shrinkage-limit, centrifuge moisture-equivalent and field moisture-equivalent, compression-index, flow-index, etc. He reports that, while the tests are not completed, the results to date indicate that considerable change in properties may be expected with a change in the cations present in the absorptive complex. The Bureau of Public Roads is starting a project to determine the properties of soils used in stabilized roads both before and after the application of chemicals. Samples are taken after the chemicals have been leached out in order to determine whether base-exchange has affected engineering properties of the binder. Preliminary results indicate that with some soils the change may be quite pronounced.

B. G. Zimmerman (University of Texas) is interested in soils as an engineering material and reports that the rate of capillary rise of water in a sand which contained 99.10 per cent SiO_2 was greater than that of a silicate which contained 63.36 per cent SiO_2, 24.42 per cent Al_2O_3, 1.45 per cent Fe_2O_3, 0.37 per cent CaO, 0.47 per cent MgO, and 9.95 per cent loss on ignition. The diameter of the particles in the two samples was the same. However, the ultimate capillary rise of the silicate was greater than that of the sand. He points out that this was probably due to cation-exchange or hydrolosis of the Al_2O_3 and Fe_2O_3, because when they hydrolyze they form colloidal solutions and thus decrease the size of the original particles. Since some of the properties of soil which influence its behavior as a structural material depend upon particle-size, it appears that these observations have significance from an engineering viewpoint.

Summary

It is evident that the investigators favor the expression of total cation-exchange capacity in milligram-equivalents to a given quantity of soil, usually taken as 100 grams, and the amount of a particular replaceable cation as a ratio to the total cation-exchange capacity. While this report is not concerned with methods, Dr. Eaton's findings to the effect that the amount of different cations found in soils is dependent upon the method employed in their determination is pertinent to this subject.

A great amount of work has been done in the laboratory to test the effect on physical properties by the substitution of different cations in both soils and colloids. Some studies have been made on field-soils in place, in which samples were taken from places in which the soil appeared to be in poor physical condition from an agricultural viewpoint and comparisons made with samples from adjacent areas in good condition. Variations in the condition in the field seemed to be associated with differences in exchangeable bases and soluble salts, other properties being similar.

Laboratory experiments in general show that such physical measurements as moisture-equivalent, permeability, deflocculation, absorption of water-vapor, heat of wetting, density during drying, hardness of crumbs of the dried soil, and cohesiveness are all increased by the substitution of sodium- or potassium-ions in the exchange-complex and are decreased by the substitution of calcium or hydrogen. Most of the investigators think that these results are applicable to field-conditions, although few tests have been made on soils in place in the field.

It is interesting to note that very little has been done on the effect of cation-substitution on the physical properties of soils as an engineering material. Likewise, little attention has been paid to the rate of extraction of water by plants, the permanent wilting-percentage, and the ability of the soil to hold water available to plants as affected by cation-substitution on the base-exchange complex.

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REPORT OF THE COMMITTEE ON UNDERGROUND WATERS, 1935-36

David G. Thompson, Chairman

Interest in problems of ground-water hydrology continues unabated. As proof of this statement it is only necessary to state that of 57 papers listed for presentation at the present annual meeting of the Section of Hydrology and of the Pacific Coast meeting of the Section on January 31 and February 1, 26 papers, or 45 per cent, related to some phase of ground-water hydrology. In this connection, attention may be called especially to the papers on ground-water presented at the Pacific Coast meeting and published in the present *Transactions*.

At this early point in his report, the Chairman should state that at about the time he usually takes the preliminary steps in compiling data for his annual report, his official duties somewhat unexpectedly took him to field-work in New Mexico and Colorado. Without the usual office facilities it has not been possible for him to make all desired contacts, and the present report of current ground-water studies is necessarily somewhat incomplete.

The personnel of the Committee on Underground Waters remains the same as last year, with one addition, Professor A. C. Swinnerton, Department of Geology, Antioch College, Yellow Springs, Ohio. He will give attention particularly to the hydrology of limestone-terranes. A statement by him in regard to research on limestone-caverns is included as Appendix A to this report. Appendix B forwarded by him is a report by E. C. Eckel on studies of the Tennessee Valley Authority relating to limestone-caves in so far as they may affect the dams and reservoirs in the region covered by that Authority. Attention may be called especially to the bibliography of caves which Professor Swinnerton is compiling, and to his requests for contributions and suggestions in regard to it.

As in other recent years, there is much interest in problems of fluctuations of the ground-water table and artesian head. The symposium on this subject presented at the present annual meeting is a partial reflection of this interest.

At the general session of the American Geophysical Union a year ago, a resolution was passed stating that "the Secretary of the Interior be requested to make provision for the collection of ground-water-level data in accordance with a complete and comprehensive plan . . ." At the request of the Water-Resources Committee of the National Resources Committee, the Division of Ground-Water of the United States Geological Survey has prepared a plan for a nation-wide program of ground-water-level observations and made estimates of the cost thereof. However, there is no item for this work included in the appropriation for the Department of the Interior for the next fiscal year, and apparently at least another year must pass before an adequate start can be made on this important program. The Water-Resources Committee has in course of publication a report on "Deficiencies in basic hydrologic data," in which, on the basis of the United States Geological Survey estimates, a concrete program for improvement of ground-water measurements is proposed. This report should be of interest to members of the Section of Hydrology.

In the meantime, the Ground-Water Division of the United States Geological Survey has endeavored to strengthen its present program of observations of fluctuations of ground-water level in connection with its current broader cooperative projects. In June 1935, there was completed for distribution a comprehensive manual describing methods essential for an adequate scientific program of observations of fluctuations of ground-water. The Ground-Water Division has undertaken the preparation of an annual report which will bring together measurements of the depth to water in typical wells in areas which are currently being investigated by it. The first report will contain summaries of the measurements for earlier years--for some localities going back many years. It will give information for 25 of the States and for the Territory of Hawaii.

It had been the hope of the Chairman that, as a project of the Committee, a questionnaire might be distributed widely to Federal and State officials to discover more definitely regions where observations of fluctuations of ground-water head are being made, the type of observations, and results thereof. Unfortunately, lack of funds for the necessary supervisory and secretarial work has prevented this study. However, in connection with more extended studies of hydrologic data of different kinds now available for all parts of the United States, the Water-Resources Committee has compiled some information in regard to programs of ground-water-level studies by Federal and State agencies. The results of this compilation, furnished by Gilbert F. White, Secretary of the Water-Resources Committee, show that in 1935 more than 6650 wells in 35 States were measured by Federal agencies, many of them in cooperation with State or other non-Federal agencies. Approximately 5000 of the wells were measured by the United States Geological Survey in cooperation with other agencies and the remainder were measured by the Corps of Engineers (875 wells in five States), the Soil Conservation Service, the Bureau of Plant Industry, the Forest Service, the National Park Service, the Bureau of Reclamation, and the Bureau of Agricultural Engineering. This compilation will furnish a starting point for a more adequate approach to the subject. The Water-Resources Committee also has published, primarily for use in planning Works Progress Administration study-projects, as part of a statement of standards and specifications of all types of hydrologic data, a special chapter on ground-water measurements.

Mention may be made of several projects for observation of ground-water level brought to the writer's attention through various sources. These are in addition to projects mentioned in previous reports. The United States Corps of Engineers is measuring several hundred wells in Illinois, Iowa, Wisconsin, and Minnesota, near the Mississippi River, to determine the effects of constructing dams and locks to improve navigation. The same agency has measured a considerable number of wells along the route of the ship canal across Florida, in connection with the very important problem of the prospective effects of digging a sea-level canal through an area of cavernous limestone in which the water-table is about 40 feet above sea-level. It has also measured wells in the Willamette Valley, Oregon, and at the site of the Conchas Dam in New Mexico.

As a part of the Rio Grande joint investigation by several Federal agencies, the United States Geological Survey is measuring several hundred wells in the Middle Rio Grande Conservancy District, extending from the vicinity of San Marcial, New Mexico, to a point some miles north of Albuquerque, and also several hundred wells in the San Luis Valley in southern Colorado. In the Middle Rio Grande Conservancy District the measurements will be used to determine the effects of drainage-ditches constructed a few years ago, as well as an aid in the inventory of input of water into the District from various sources and output from it. In the San Luis Valley the observations will be used both to determine the effects of drainage, and the possibility of benefits by proposed additional drainage-projects. In some parts of this Valley sub-irrigation is practiced and sufficient water is put on the ground to raise the water-table 20 to 30 feet or more above its original natural level. Apparently, as a result of this liberal use of water in part of the intake-area, there has been an expansion of the area in which artesian wells flow naturally. This is in contrast to many areas where there has been a decline in artesian head and decrease in the area of artesian flow. In both areas many wells have been measured at irregular intervals in past years by several agencies, including the United States Bureau of Reclamation, the United States Bureau of Agricultural Engineering, the office of the State Engineer of New Mexico, the Middle Rio Grande Conservancy District, and the office of the State Engineer of Colorado.

Information in regard to several other well-measurement projects is given in papers presented in the symposium on the current program.

In the phase of hydrology as applied to oil-fields, Dr. F. H. Lahee reports that studies have been carried out to determine the rise of water-level in the East Texas Field and concomitant decline in oil- and gas-pressure, and to estimate the expansion of oil and its dissolved gas, still remaining in place.

Also related to hydrologic problems in oil-fields as well as general problems of permeability is the following information furnished by Dr. Morris Muskat in regard to hydrologic studies by the Gulf Research and Development Corporation:

"I have but little to report on the progress of underground-water research during the past year, except some by-product studies that have been carried on at our own laboratory. I refer to them as by-products quite intentionally, since most of our activities during the last year have been concentrated on the investigation of the flow of gas-liquid mixtures through sands which is, of course, as you know, the major hydrodynamic problem of the subject of oil-production. We feel that the analytical study of the motion of homogeneous fluids through porous media, such as liquids and gases, has been fairly well completed with respect to their applications to the oil- and gas-industries and such phases of civil engineering as dam-construction. I have recently completed a book entitled The flow of homogeneous fluids through porous media' in which the various analytical solutions to these problems and the methods of measuring permeabilities and porosities are presented in detail.

"What we have done last year along these lines consists, therefore, essentially of what might be called left-overs, which were studies for the purpose of rounding out the general subject of the flow of homogeneous fluids through porous media. Some of these results have been published in the following papers: (1) 'Electrical conduction models for the solution of water-seepage problems,' by R. D. Wyckoff and D. W. Reed (Physics, v. 6, pp. 395-401, 1935); (2) 'The seepage of water through dams,' by M. Muskat (Physics, v. 6, pp. 402-415, 1935); and (3) 'The seepage-flux under dams of extended base-width and under coffer-dams resting on permeable strata of finite thickness--I,' by M. Muskat (Physics, v. 7, pp. 116-125, 1936).

"The completion of the numerical work on the problem of seepage of water through dams developed by G. Hamel, and to which I referred in my last year's report, has since been published in a paper by G. Hamel and D. Gunther (Zs. Angewandte Math. Mech., v. 15, pp. 255-265, 1935). A different type of problem which was investigated in this laboratory during the last year, and which, while not directly concerned with the problem of underground-water flow, is nevertheless of interest with regard to the question of the origin of artesian pressures, is a paper published by H. G. Botset and D. W. Reed in the Bulletin of American Association of Petroleum Geologists (v. 19, pp. 1053-1060, 1935), entitled 'Experiment on compressibility of sand.'"

Ground-water hydrologists will await with interest the publication of Dr. Muskat's book on flow of homogeneous fluids through porous media. It is interesting to note how the studies of Dr. Muskat and his associates on problems relating to the petroleum-industry have led farther afield to problems of seepage of water through and beneath dams.

Field-studies by L. K. Wenzel on Thiem's method of determining the permeability of water-bearing materials have been reported in preliminary form at previous meetings of the Section of Hydrology. These studies are now described in more detail by Mr. Wenzel in Water-Supply Paper 679-a, recently published by the United States Geological Survey.

A phase of geophysical studies that is becoming of increasing interest to ground-water hydrologists is the use of electrical-resistivity methods to obtain some idea of underground conditions. During the last year or two such methods have been used by the Illinois, Missouri, and South Dakota Geological Surveys, and other agencies to determine the position of water-bearing gravels. Studies of the use of electrical-resistivity methods in ground-water investigations have also been made by C. A. Heiland of the Colorado School of Mines and M. King Hubbert of Columbia University. Robert B. Simpson has submitted a statement calling attention to the desirability of using geophysical methods to determine the location of water-bearing gravel-beds near Fargo, North Dakota. At this locality drilling in two small areas has revealed the presence of buried pre-glacial valleys and electrical-resistivity methods should be well suited to determine the course of these valleys over a larger area.

During the past year the United States Geological Survey, in cooperation with the United States Bureau of Mines, has been using electrical-resistivity methods in an investigation of the ground-water supply in the vicinity of El Paso, Texas, and in the Territory of Hawaii. The United States Bureau of Mines has carried on similar work in Nevada. The United States Geological Survey, in cooperation with the New Jersey State Water Policy Commission, has recently purchased resistivity-apparatus to be used particularly in an effort to delineate the boundaries of bodies of salty ground-water invading well-fields in the vicinity of Atlantic City, New Jersey.

Brief reference may be made to several miscellaneous matters as follows:

A preliminary announcement of the International Conference on Soil Mechanics and Foundation Engineering, to be held at Cambridge, Massachusetts, in June 1936, includes among other topics to be considered the following of interest to ground-water hydrologists: Ground-water movement and seepage; reports from soil-mechanic laboratories on testing apparatus, technique of testing, and investigations in progress; exploration of soil-conditions and soil-properties.

The report on the Progress-Conference on Water-Conservation held in Los Angeles March 13 and 14, 1935, under the auspices of the Committee on Conservation of Water, American Society of Civil Engineers, contains a paper on "Economic limits of conservation of flood-waters by spreading," by Kenneth Q. Volk. Another paper, by Harold Conkling on "Law of underground waters," presented at the same meeting, was published in the proceedings of the American Society of Civil Engineers for April, 1936.

A notable volume published during the year was "Hot springs of the Yellowstone National Park," by E. T. Allen and Arthur L. Day, under the auspices of the Carnegie Institution of Washington. This beautifully illustrated report gives much information on the subjects of thermal activity, distribution and quantity of the underground water, quality of the water in the Yellowstone National Park, and theories of the cause of geysers.

During the year there has been completed a report by Norah D. Stearns, Harold T. Stearns, and G. A. Waring, on all known thermal springs and thermal-spring localities--about 1000 in number--in the United States. This is to be printed as a Water-Supply Paper of the United States Geological Survey. Also for the Geological Survey, D F. Hewett is pushing to completion a report on geology and hydrology of the Warm Springs, Georgia, Area.

Ground-water hydrologists will find much of interest in the report by W. G. Hoyt and others, "Studies of relations of rainfall and runoff in the United States" (U.S. Geol. Surv. Water-Supply Paper 772), particularly sections that consider the role of ground-water in influencing the flow of streams.

The reports of the National Bureau of Standards entitled "Current hydraulic laboratory research in the United States" list several ground-water projects. Among those which have not already been mentioned in previous reports or described in papers read before the Section of Hydrology the following may be mentioned. More detailed information as to scope of the projects, etc., may be obtained from the list of the National Bureau of Standards for the following: Charles H. Lee, Relation of permeability of granular materials to particle-size; Mississippi River Commission, Study of hydraulic gradient and flow-lines in levees; G. M. Fair and L. P. Hatch, Hydraulics of flow of water through sand--continuing studies, using small-size tubes containing sand of different structure; University of California College of Agriculture, Studies on the effect of depth to water-table upon the loss of water from the soil-surface, and movement of moisture through soils; E. F. Wilsey and C. C. Wang, Iowa Institute of Hydraulic Research, An analytical and experimental study of the flow of water through sands--an abstract of a dissertation by Wilsey, giving partial results, is contained in the National Bureau of Standards "Current hydraulic laboratory research in the United States" (Bull. III-2, pp. 69-70, 1935);T. P. Tsui, Iowa Institute of Hydraulic Research, Laboratory study of ground-water profiles (brief progress-report in National Bureau St. Bull. No. III-a, p. 64, 1935); Lieutenants Besson, Kumpe, Lincoln, Powers of United States Corps of Engineers, Study of seepage through earth-dams on pervious foundations (studies at Massachusetts Institute of Technology); United States Bureau of Reclamation, Study of percolation through, and stability of, earth-dams under a changing head; Prof. F. T. Mavis, Iowa Institute of Hydraulic Research, Continuous records, since 1924, of ground-water levels, in connection with other hydrological studies of Ralston Creek Watershed; W. E. Code, United States Bureau of Agricultural Engineering, Study of size of intake-openings and well-screen diameter in relation to the yield of wells; R. E. Horton, Position and migration of ground-water divides in permeable deposits.

The Annotated Bibliography of Economic Geology includes a section on underground water, in which brief abstracts are given of the current publications relating to this subject in all languages; this Bibliography is published twice a year by the Economic Geology Publishing Company, Urbana, Illinois, and is prepared under the auspices of a committee of the National Research of which Professor Waldemar Lindgren is chairman. The abstracts concerning underground water are prepared under the direction of Dr. A. N. Sayre by different members of the Ground-Water Division of the United States Geological Survey, a major part of the work in recent years being done by V. C. Fishel. Professor Lindgren has taken much personal interest in the section on underground water and has contributed to it chiefly by calling attention to many publications in German and other foreign languages that might otherwise have been overlooked. All workers in hydrology should have access to this Bibliography.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--RESEARCH ON LIMESTONE-CAVERNS

A. C. Swinnerton

General--James H. Gardner, Tulsa, Oklahoma, who published during the year a paper "Origin and development of limestone-caverns" (Bull. Geol. Soc. Amer., v. 46, pp. 1255-1274), has continued the study of some aspects of the problems mentioned in that paper in connection with the Carlsbad Cavern. Correspondence with M. E. Roberts, petroleum-geologist of Odessa, Texas, has brought out additional evidence regarding the recent age of the Cavern and its relation to uplift along the sides of the Guadalupe Mountains which has tilted the stalactites from a vertical position.

A. C. Swinnerton, Yellow Springs, Ohio, has continued study on the relation of the general theories of cavern-origin to structural control reported in abstract in the Proceedings of the Geological Society of America for 1934, page 115. He is also engaged in compiling a bibliography of caves. Contributions and suggestions for the bibliography will be welcome.

Pennsylvania--R. W. Stone, Harrisburg, Pennsylvania, reports that Bulletin G 3 of the Pennsylvania Geological Survey terminated his official field-work on caves. He writes that since that time about 20 caves not mentioned in Bulletin G 3 have come to his attention and that "much work could be done on the origin of caves and their curious features, but the report satisfies present needs . . . . Students looking for thesis-subjects might find abundant material for consideration in our caves."

Tennessee Valley Authority--See Appendix B by Edwin C. Eckel, Chief Geologist.

Virginia--William M. McGill, Assistant State Geologist, Virginia Geological Survey, Charlottesville, Virginia, reports that he has done no further work on caves in Virginia since the publication of Bulletin 35 of the Virginia Geological Survey. He hopes in the near future to resume studies of different types of travertine formations or peculiar growths in several of the caves of Virginia.

National Park Service--Earl A. Trager, Chief of the Naturalist Division, reports that several geologists of the National Park Service are studying features of caves in approximately 20 areas. J. Volney Lewis is preparing a descriptive manual of all types of caves for use in the many National and State parks and monuments which include caves. A brief paper giving a summary of the studies of E. R. Pohl in the Mammoth Cave Region of Kentucky follows as Appendix C.

Antioch College,
Yellow Springs, Ohio

APPENDIX B--GEOLOGIC WORK OF THE TENNESSEE VALLEY AUTHORITY ON LIMESTONE-CAVES

E. C. Eckel

The Division of Geology of the Tennessee Valley Authority is necessarily keenly interested in the question of limestone-caverns in its relation to various engineering projects of the Authority. Caves affect our work in a number of different relations and a very large fraction of our field-work has been involved in one way or another in the question of such caves. We are not as yet prepared to issue a special report on this subject, but such a report will, it is hoped, be possible within the next year or so. At the moment it will perhaps be clearest if the work be briefly described in its relation to particular dams.

Aurora Dam--At Aurora and points below it to Paducah, the question of caverns has not as yet bothered us. Our difficulties there center around deep weathering and channels down almost to the present sea-level. If these foundations are ever utilized, we will probably find natural caves reaching into these channels at varying depths, but as yet none such has been found in the drilling and the matter is not of immediate engineering importance to us. The work in this region has been in charge of Roger F. Rhoades.

Pickwick Dam--Pickwick Dam is built on relatively insoluble limestone and no caves were struck at any level.

Wheeler Dam--The foundation of Wheeler Dam is on insoluble limestone but the abutments and the higher land around the banks or the reservoir are on the very soluble Tuscumbia Limestone.

This has involved extensive work by E. L. Spain, Jr., and his assistants in tracing the probable courses of underground streams. These courses are broken at intervals by sinks, and a great many land-damage claims, as well as water-supply questions, have depended for their solution upon careful geologic work. The caves in this region never reach more than 20 feet below the existing river-bottom. Caves, sinks, and underground sinks are oriented primarily along joint planes.

Guntersville Dam--The Guntersville Dam and its reservoir are in the very soluble Bangor Limestone. The work was done there by Robert M. Ross, under my personal direction. It involved tracing of one long cave which Ross entered for one-half mile or so, and of determining the connection of that cave with sinks at a higher level. In that connection I had careful sampling done by Ross of the beds replaced by the caves and of the beds which form its floor and roof. The analyses showed that the ultra-soluble limestone here contained around 90 to 97 per cent lime-carbonate, while the relatively insoluble floor and roof-beds carried from 80 to 90 per cent carbonate. In the Guntersville region I might note that there is very deep decay, reaching down in some places to 80 feet below present water-level.

Chickamauga Dam--At Chickamauga, where the work was carried on by Roy Caldwell under my immediate direction, we have found very few caves but we have found deep weathering at a number of points down to levels 75 to 100 feet below the present river-level. The limestone-beds involved in this are steeply inclined, and the deepest weathering takes place partly in certain very soluble beds, and partly along joint planes.

Norris Dam--At Norris Dam I have personally kept track of the cave-situation since Swinnerton and Keith reported on the area. In our foundation-work we found neither weathering nor caves existing more than 10 to 15 feet below the present river-bed. All of our difficulties there have arisen from older cave-systems which exist at several levels above the present river, ranging from 100 to 300 feet above its bed. On the western abutment these several series of caves are interconnected by almost vertical chutes. They are oriented along two different series of joint planes and obviously are not related to the present course and level of the river, but to some older stages of the river. Caves further up in the reservoir which have been studied more particularly by Mr. Cullison and his assistants show the same relations of level and alignment. I might note that all of these caves in the Norris region are either in the Knox Dolomite or some of the purer phases of the Chickamauga Limestone.

Summary

While I hesitate to commit either the Division of Geology or myself personally in any final way, it seems to me that several points of general interest have been developed by our extensive geologic and engineering work.

(1) The depth of channeling and of weathering at Aurora and lower river-points suggests previously existing higher land-level, perhaps 300 feet above the present level at some points. This, however, is involved in questions of the geologic history of the region, and I am therefore not accepting it as definitely proven at the moment. From Aurora upstream as far as Wheeler Dam we have no evidence that the land ever stood much higher than at the present time, that is, we have no weathering or caves which extend more than 20 feet below the present river-bottom. In the Guntersville-Chickamauga region, on the contrary, we do have deep weathering extending as far as 100 feet below the present river-level. This seems to me to be evidence of previous land-uplift. We have not as yet found any large cave-system at these deep levels. In the Norris region there is equally neither weathering nor caving in the 15 feet below the present river-level. Out of this whole mass of records we get some idea that there has been differential warping in the Tennessee Valley region during very recent geologic time.

(2) In the areas such as Guntersville and Norris, where limestone-banks rise steeply from the river, we have several series of cave-levels. Each series seems to have been operative at a temporary base-level, that is to say, in each series there are long strips in which a cave-bottom will not vary more than a few feet in elevation. Above this there will be a long cave lying at a base-level at perhaps 100 feet above the first. The series seem to me to indicate stages in the rise of the land during quite recent periods, that is, during the Pleistocene for instance. My feeling is that each series represents a stage in such rise. Our only evidence as to temporary downward movement is gathered from certain swamp deposits which are not quite in the Tennessee Valley region.

(3) In all of our caves the controlling factors are obviously purity of the stone and its coarseness of grain or porosity. When rocks lie at low angles the caves tend to occupy soluble beds while the vertical connections with other cave-series are invariably down joint planes.

At some points indeed we have very close series of narrow high caves which in reality are in most instances really merely fissures extending through the rock-surface.

Tennessee Valley Authority,
Knoxville, Tennessee

APPENDIX C--GEOLOGIC INVESTIGATIONS AT MAMMOTH CAVE, KENTUCKY

E. R. Pohl

Field-work on the areal geology and the geologic structure of the proposed Mammoth Cave National Park has been in progress for some months. To date, a little more than two-thirds of the 75,000 acres included in the proposed maximum boundaries has been mapped. The remainder of the area is to be completed this fall. It is contemplated that the map will be published by the United States Geological Survey upon submission and acceptance.

Investigation preliminary to the proposed opening of a portion of Mammoth Cave separated by collapse from the main part of the Cave has been in progress. At the present time Mammoth Cave is entered through an opening caused by this collapse. The location of this collapse-entrance is a short distance from the original entrance to the Cave, this being at what is now known as Dixon Cave.

The saltpeter vats and workings of Mammoth Cave, Dixon Cave, and Longs Cave represent an important phase in the history of the use of certain products of ground-water deposition. Study in preparation for a restoration of these workings is also under way.

Little precise information concerning the numerous caves of the proposed Park has been available in the past. From time to time it has been possible to record observed facts concerning the geology and hydrology of the many little-known caves within the Park boundary.

Until recently accurate large-scale maps of the numerous caves within the Park were not available. At present a careful and extensive survey of Mammoth Cave is being made by a United States Geological Survey party and it is possible that the same procedure may be followed in several additional caves. Such maps, in conjunction with the geologic and structural maps, will aid in interpreting the physiographic history of the region.

Studies

For some time it has been recognized that the various galleries of the Kentucky caves lie at several distinct "levels." There has been little attempt to correlate these levels in the different caves of the region because of the lack of engineering data.

Origin of sand-deposits in Kentucky caves--The problem of correlating the cave-levels is complicated by more primary considerations than the lack of engineering data. The presence of thick deposits of stream-transported sand, gravel, and silt within the cave-galleries forms one of the greatest obstacles in the way of determining the true elevation of stages in the base-leveling of the region. In the large avenues of Crystal Cave and Longs Cave these deposits have an observed thickness of upward to 100 feet at locations where they are exposed in section. On preliminary investigation it seems obvious that the gallery-excavation had been accomplished before the influx of this accumulation. Where these deposits have been removed, as has occurred at the positions of cross-caves near the bases of the larger passages, the channel-walls show conclusive evidence of solutional activity. The predominance of solution over abrasion in these passages could only have been effected during times of slowly moving waters in them. The very presence of the sand leads to the conclusion that it was carried by more rapidly moving water at a later date. If conditions of rapidly moving water had continued for any length of time previous to the deposition of the sand the solutional effects upon the gallery-walls would have been obliterated by such excellent tools as are found in these deposits.

The writer's conviction, as yet not definitely proved, is that this sand and clay represents material carried by exceptionally high waters during the several Pleistocene interglacial stages when the heavily laden streams were carrying off the excess water from the receding ice-sheets just to the north. In fact, it is his opinion that the entire formation of the caves of the Mammoth Cave Region hinges on the changes in the rate of down-cutting of Green River and its subsurface-tributaries, as influenced by the varying quantity of water available in the changing climates of the Pleistocene.

These variations in the rate of down-cutting of surface- and subsurface-streams would have been dependent on postulated variation of the strand-line during the glacial epochs. It follows that the broad chambers of the various cave-levels were formed at periods of arrested down-cutting and that the high narrow passages were formed during periods of rapid down-cutting.

The streams, both surface and subterranean, became increasingly loaded upon the rise of the strand-line with the return of ice-locked water to the oceans and great quantities of debris were laid down in the already enlarged galleries by back-flooding. Deposition could have been accomplished in such avenues only in times of exceptional flood by a reverse of flow. Stratified beds of sand examined in the caves indicate such a reversal through an interpretation of the direction of foresetting.

It is doubtful that floods under normal conditions could have produced deposits of sand within the caves to such great height above a given cave "level" (up to 100 feet). The flood-plain of Green River lies some 28 feet above its low-water stage. The highest record for Green River at Mammoth Cave Ferry occurred in 1913 when it rose to a height of 49 feet above low-water stage.

In discussing the origin of the Cave sand-deposits it seems reasonable to believe that normal drainage-level during one of the Ice-Age intervals occupied a position somewhere near the floor of a particular gallery in which these deposits occur. This premise is upheld by a study of present conditions in the lowest level of Mammoth Cave today. The portions of the Cave now occupied by water are readily accessible to Green River as it rises during flood. Such bodies of water as Echo "River," "River" Styx, and Roaring "River" have little or no flow in them except under the influence of the rising or receding waters of Green River. This is because these parts of the Cave (and in fact all of Mammoth Cave) lie below a ridge and not beneath a valley. Other subsurface water-courses without apparent connection with Mammoth Cave receive the drainage of Bruce Hollow, Doyle Valley, and Eaton Valley. These are the depressions that flank the Mammoth Cave Ridge. The rise and fall of the waters in Mammoth Cave coincide with that of Green River.

These cave-deposits could not have resulted from normal conditions nor from floods during a normal period (such as exists today) and the explanation of at least five periods of exceptionally high flood-waters must be sought.

The theory presented here offers another alternative to Davis' hypothesis of deep-seated, sub-water table solution, the main objection to which is the actual disposition of the Kentucky caves into decided "levels" despite the absence in the limestone succession of similarly spaced resistant or insoluble beds.

Influence of resistant beds on cave-development--In areas under the process of active dissection the development of large cavern-galleries is impossible at any considerable distance from the major drainage until the water-table becomes adjusted to base-level. This may be accomplished in a region of uniformly soluble beds through the headward erosion of a branch-work system of subsurface-streams similar in all respects to surface-drainage. However, a thick succession of uniformly soluble beds is seldom found. The most usual interruption of uniformity in the succession is the presence of one or more impervious or resistant beds. In a region of gently dipping beds such strata, by resisting down-cutting, produce much the same effect as that of final stream-adjustment to base-level. This is true only in cases where no impervious cap is present such as might form a zone of concentrated movement at drainage-level or in cases where the impervious bed lies at a considerable height above the water-table. In a water-bearing bed below an impervious stratum artesian conditions become effective upon its being tapped in a down-dip direction. When such a zone is tapped by the down-cutting of a stream, solution and excavation tend to act in an upward direction where the hydrostatic head is sufficient to cause a volume of discharge. Such conditions would produce broad and low cavernous galleries near the points of discharge which increase in height and narrow in width in the direction of the divides.

An important observed fact in regions of gently dipping beds is that the points of discharge of subsurface-drainage are found where the meanders of a surface-stream are convex in an up-dip direction. This is primarily true because such positions first tap any static water held in check by a "cap-rock." Such water being first tapped at these positions tends to initiate the principal paths of subsurface-flow at these points.

The origin and growth of cave-gypsum--Gypsum does not occur in large quantities as a cave-deposit generally, but is quite characteristic of the larger of the caves of central Kentucky and southern Indiana. This subject is being treated exhaustively in a paper in preparation which was reported in abstract at the last meeting of the Geological Society of America.

The origin of pits and domes--A striking feature of the caves of central Kentucky is seen in the numerous "pits" and "domes." These are narrow, vertical shafts or tubes sometimes having a height of over 100 feet. Several theories as to their origin have been advanced, none of which fully explains all the features seen in them. This problem forms the subject of a paper which has been submitted to the Geological Society of America for publication.

Observations on climatic conditions in caves--Recording instruments have been placed in Mammoth Cave to secure data on atmospheric conditions. The first results indicate that barometric pressure varies nearly precisely with that outside but without the abrupt fluctuation of the latter. Humidity-conditions seem to remain exactly constant for particular locations and are always in excess of 75 per cent. Temperature-conditions appear to remain constant also for individual stations.

National Park Service,
Washington, D. C.

REPORT OF THE COMMITTEE ON DYNAMICS OF STREAMS, 1935-36

Lorenz G. Straub, Chairman

A number of organizations have recently been quite active in fields closely related to that of the Committee on Dynamics of Streams. Among these are some recently organized groups having fairly clear-cut purposes in view.

The International Association for Hydraulic Structures Research was founded in September 1935, with the objective of promoting international cooperation of persons interested in research related to hydraulic structures and to enable an exchange of views. It is apparent from the membership forming the nucleus of the Association that primary attention is likely to be given to the application of hydraulic models to the solution of various stream-dynamics problems such as the regulation of rivers, the design of dams, harbors, etc. Largely because of the geographical distribution of its members throughout the world the Association unquestionably will do much toward accelerating the development of methods of analyzing river-regulation problems.

A very prolific organization has been developing in Russia under the name of the Scientific Institute of Hydrotechnics. It publishes Transactions periodically, devoted largely to mathematical and experimental treatments of stream-flow. The discussions are presented in Russian and for the most part are summarized in English.

The Special Committee on Hydraulic Research of the American Society of Civil Engineers, which was organized about two years ago, is devoting its attention largely to investigations in open-channel flow. It is preparing a set of standard symbols for use in hydraulic research, also a manual on hydraulic-laboratory practice, primarily as related to open-channel-flow investigations.

Other organizations whose activities are related to those of the Committee include: The Committee for Research on Hydraulic Friction of the National Research Council; the Committee on Symbols and Abbreviations of the American Standards Association; the Hydraulics and Applied Mechanics Section of the American Society of Mechanical Engineers; and the Committee on Applied Hydraulics of the Society for the Promotion of Engineering Education.

One of the most valuable and useful publications having as its purpose the exchange of information on hydraulic research is that of the Hydraulic Laboratory Section of the National Bureau of Standards. During the past year its Bulletin has taken on a particularly commendable form.

Several committees are working on the standardization of symbols and nomenclature. There is definite evidence of a coordinated effort of these various groups, as well as the Committee on Dynamics of Streams, to produce sets of standards which will not conflict within related fields of hydraulics.

A large number of papers related to stream-dynamics has appeared during the past year dealing with sediment-transportation, varied flow in open channels, turbulence, etc. Considerable progress is especially evident in the analysis of the internal mechanics of flow. The laboratory-approach has been making rapid headway. With the present interest and rate of progress in stream-dynamics, certainly a great deal of development is to be expected in the immediate future.

University of Minnesota,
Minneapolis, Minnesota

REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1935-36

C. S. Howard, Chairman

The membership of this Committee was not changed during the past year.

A publication has appeared during the year giving the analytical data assembled for and used as a basis for Bulletin 40 of the Department of Public Works, California. This new publication, printed as 40-A, is entitled "Detailed analyses showing qualities of irrigation-waters." Analyses are given for both surface- and ground-waters.

The chemical composition of the water in Yellowstone National Park was reported by Allen and Day in Publication 466 of the Carnegie Institution of Washington entitled "Hot springs of the Yellowstone National Park." This report gives analyses and description of the types of waters and their distribution throughout the Park, in connection with discussions of the composition of sinters and other deposits formed by these waters.

In a study of the occurrence of selenium in soils and plants the United States Bureau of Chemistry and Soils has collected a number of samples of water for the determination of selenium in the waters used for irrigation and in the drainage-waters in a number of areas. The concentration of selenium was rather high in the waters from some of the areas particularly in the water flowing in the drainage-ditches from certain of the irrigated fields. Selenium was present in considerable quantities in the salt crusts and deposits formed in fields on the evaporation of the water used for irrigation.

The investigation of the corrosion of ferrous metals by soils has been continued by the National Bureau of Standards during the past year. The chief factors inducing corrosiveness are high concentrations of soluble salts, especially those of the alkali-metals, and high acidity, both factors tending to increase the solubility of the hydroxides of iron and to prevent the formation of protective layers of corrosion-products. Corrosion was relatively slight in soils in which the soluble material consists chiefly of the bicarbonates of calcium and magnesium and in well-aerated soils in which the hydroxides of iron are precipitated in immediate contact with the corroding area. A laboratory-study was completed on the corrosion of steel in 47 soils, the corrosiveness of which is definitely known from field-studies. The study was made by means of a cell in which anode and cathode were of the same ferrous material and the electrolyte was moist soil. By providing for the aeration of one electrode while excluding air from the other, the cell was enabled to develop its own electromotive force. From measurements of voltage, current, resistance, polarization, and the loss of weight of test-specimens and from analyses of water-extracts of the soils, it was possible to account generally for the differences in corrosiveness of the soils. The work of the past 14 years has produced data for the development of specifications for the protection of underground pipes.

Mr. Case has submitted analytical data showing the chloride-content in some of the streams draining the area of the Permian red beds. Most notable of these rivers are Red River, which forms the southern boundary of Oklahoma, and the Cimarron River, which empties into the Arkansas River in the northern part of the State. These streams were selected to illustrate the effects of the Permian outcrops because of the fact that from the sampling points to the headwaters there is no possible effect from oil-field pollution. The chloride-content for a number of samples from these streams are given in Table 1.

The sealing of abandoned mines in West Virginia, Pennsylvania, and Ohio has been continued during the past year in an effort to improve the quality of the water in streams which were getting drainage from these mines.

Mr. Eaton presented a paper (printed later in this volume) at the 1936 Pacific Coast Meeting of the Section of Hydrology entitled "Changes in the composition of ground-waters resultant to anaerobic sulfate decomposition and the attendant precipitation of calcium and magnesium."

Dr. G. A. Abbot of the Department of Chemistry, University of North Dakota, has made a survey of the fluoride-content of the deeper ground-waters in North Dakota with special reference to the artesian waters of the Dakota Sandstone Basin. He found that the distribution of the fluoride is in well-defined zones which could be mapped to show areas where the waters have the same fluoride-concentration. For those areas in which the fluoride is a definite problem the concentration of fluoride ranged from three ppm in a rather large area to nearly ten ppm in a small district. It is hoped that the survey may be extended to adjacent parts of South Dakota and Minnesota.

Table 1--Chloride in samples collected from three rivers in Oklahoma in parts per million

[A from Red River near Altus, Oklahoma; B from North Fork of Red River near Altus, Oklahoma; C from Cimarron River near Crescent, Oklahoma]

Date	A	B	Date	C
Aug. 12, 1935	2100	2390	Nov. 12, 1934	4150
May 13, 1935	1820	3792	Dec. 20, 1934	5730
June 17, 1935	728	2795	Feb. 5, 1935	5860
July 18, 1935	796	4150	Mar. 15, 1935	2053
Sep. 11, 1935	428	2208	May 9, 1935	5330
Oct. 15, 1935	1695	2392	June 26, 1935	1120
Nov. 14, 1935	2559	2236	Aug. 12, 1935	5650
Dec. 13, 1935	2887	5380	Sep. 17, 1935	1826
Jan. 13, 1936	1696	4420	Oct. 15, 1935	3695
Feb. 10, 1936	2565	3820	Nov. 13, 1935	6106
Mar. 7, 1936	2355	2060	Jan. 13, 1936	9440
			Feb. 18, 1936	7440

U. S. Geological Survey,
Washington, D. C.

SYMPOSIUM ON FLUCTUATIONS OF GROUND-WATER LEVEL

INTRODUCTION: SOME PROBLEMS RELATING TO FLUCTUATIONS OF GROUND-WATER LEVEL

David G. Thompson

(Published with the approval of the Director, U. S. Geological Survey)

When the program for the meeting of the Section of Hydrology a year ago was in preparation, it was suggested that a symposium be presented on the subject of the effects of the recent drought on ground-water levels. The proposal was not carried out largely because at that time not enough accurate information on the subject was yet available. It has, however, seemed that this year a worth-while group of papers could be developed on the broader subject of fluctuations of ground-water levels.

In a few parts of the country, records of water-level go back for many years. Observations are reported for Brooklyn as early as 1834 and a contour-map of the water-table farther east on Long Island was published in 1867. However, in spite of these and other early observations and a great amount of technical work on the subject in recent years, there is abundant evidence that comparatively few persons have any adequate understanding of the complexity or significance of fluctuations of ground-water levels. In view of this fact and of the fact that probably more than half of the people of this country obtain their water-supplies from underground water, and considering the psychological factor, it is perhaps not surprising that in periods of unusual drought there are rumors of persistent, permanent, and irremediable drop of the water-table or artesian head.

Studies of fluctuations of ground-water levels are probably of most importance in connection with quantitative studies of the supply available for various purposes--whether for public or industrial supply of cities, for irrigation in agricultural regions, or merely for small domestic supplies in rural areas. In quantitative studies, observations of fluctuations of the water-table or artesian head give useful information as to recharge of the formation, the discharge by seepage, spring-flow, evaporation and transpiration, the permeability of the formation, the effects of pumping, and other factors involved in the determination of its safe yield. However, observations of such fluctuations are proving to be valuable in a variety of other studies. These include studies of the relation between rainfall and fullness of the ground-water reservoir as an aid to predicting the low-water flow of streams. Although not much attention has yet been given to the opposite phase of the problem, the question may be raised as to whether fluctuations of the water-table may also be used to show danger of flood-conditions when heavy rains produce an unusual saturation of the ground. Other studies relate to the effects of the artificial disturbance of the natural conditions affecting ground-water recharge and discharge, and hence the flow of surface-streams. These include the building of dams and locks which may produce either advantageous or damaging rise of the water-table upstream from these structures and opposite effects downstream from them; the construction of drainage-ditches and canals, and works to change the courses of rivers, all of which may lower the water-table; the development of irrigation and sub-irrigation projects, which may cause the rise of the water-table generally for useful results, but in many areas producing the opposite effect when water-logging and spoilage by alkali occur; and efforts to conserve water by spreading the flood-flow of streams that otherwise would be wasted. Fluctuations of water-level have also yielded incidental information of interest to geophysicists in regard to problems of the elasticity and compressibility of water-bearing formations, of transmission of earthquake-waves, and of tidal phenomena.

It is essential that accurate distinction be made between the water-table and artesian conditions, and that correct use be made of the term water-table and its artesian counterpart, namely, the piezometric surface. Certain fundamental differences are observed between fluctuations of the water-table, under non-artesian conditions, and of the piezometric surface under artesian conditions. Under water-table conditions there is generally no impediment to rainfall-penetration and the water-table generally shows relatively direct response to rainfall. In different parts of the country the amount of fluctuation of the water-table may range from only an inch or two to many feet, and the type of fluctuation-curve may differ considerably from region to region depending upon differences in the quantity and distribution of the precipitation, the intensity of the winter season, the character of the soil and vegetation, the permeability of the water-bearing beds, the depth to water, and artificial conditions. Thus, in Lea County, New Mexico, where the rainfall is low and most of it occurs in summer, the annual fluctuation, as observed by water-stage recorders, has amounted to only an inch or two and over periods of several weeks the movement has been almost imperceptible. In contrast, three observation-wells near Washington, D. C., have shown an average fluctuation in a period of about four years of more than 12 feet; and Cullings reports a fluctuation of 16 feet (see paper in present Transactions). In a shallow well in fine material near Runyon, New Jersey, the water-table rises after each rain in the approximate ratio of about one foot of rise for each inch of rain, and begins to drop almost immediately as soon as the rain ceases; so that the water-level is continually moving up or down through an annual range of three or four feet. But the effect of rain is greatly minimized and sometimes obliterated in the growing season, when the rain-water is largely dissipated by evaporation and transpiration. The highest level of the year is generally reached just before the growing season begins and the lowest level near the end of the growing season. In contrast, in the same region where the water-table is from 35 to 50 feet below the surface the highest level is not reached until midsummer and the lowest level correspondingly later. The lag is obviously due to the longer time required for penetration to the greater depth. The writer knows of no adequate published observations to show the amount of lag, where the water-table lies at a greater depth. Observations now in progress in Nebraska under the direction of L. K. Wenzel, reported in part in the present Transactions, may yield information on this problem.

In contrast to water-table conditions probably most artesian wells do not show fluctuations of head in response to fluctuations in rainfall. Presumably such fluctuations would be most noticeable near the intake-area, and for a number of reasons would become less and less at points farther and farther away from the intake. This problem is one that merits further study.

There is also a marked difference in the type of fluctuation under non-artesian conditions when wells are pumped. Where water-table conditions exist, water is actually drained from the formation in the vicinity of the pumping well under ideal conditions in a circular area. As pointed out by C. V. Theis [see 1 of "References at end of paper], the diameter of this drained area should increase slowly, but indefinitely, as long as pumping is continued. However, presumably at a given distance from the pumping well there is no drop in the water-table until drainage of the cone of depression has progressed to the locality in question. Because this involves an actual change in volume of water in storage, this occurs relatively slowly. Thus, when certain shallow wells drawing from fairly permeable material along Croton River, New York, are pumped, a recorder on an observation-well about 475 feet distant does not show any downward movement for three to five hours after pumping begins, and there is a corresponding lag in the rise when pumping ceases.

In contrast, where true artesian conditions exist, the formation around the well is completely saturated and generally no draining occurs when a well flows naturally or is pumped. The water moves in a closed pressure-system, and the effects of pumping, evidenced by changes in pressure, are rather quickly transmitted to considerable distances. Thus, in highly permeable materials in the Puchack Run well-field of the Camden, New Jersey, Water Department and in the moderately permeable 800-foot sand at Atlantic City, first indication of pumping has been observed in observation-wells about 1000 and 300 feet distant, in the respective localities, in a very few minutes. Also, because the water is confined, as in a pipe-line, within a reasonably short period the decrease in pressure during pumping may be transmitted for long distances. Thus, there is good evidence that seasonal changes of a magnitude of about four or five million gallons in the rate of pumping from wells in Atlantic City and other cities south thereof causes a change in head of several feet in a well at the Atlantic City well-field in Pleasantville, about five miles from the nearest pumping well [2]. As another example, when wells in the Flushing well-field of the City of New York Department of Water Supply, Gas, and Electricity are pumped at a rate of about three and one-half million gallons a day, the water-level in an observation-well in the abandoned Bayside well-field about 2-1/2 miles distant, drops as much as 12 feet [3]. These examples are especially significant when it is remembered that Slichter and others, in formulae for determining the effect of pumping, have stated that it is sufficient to consider the radius of the cone of influence of a pumping well to be only 600 to 1000 feet [4].

As under water-table conditions, lag has been observed in artesian wells but the lag is believed to be due to a different cause, namely, to the factor of elasticity and compressibility of the water-bearing formation. Observations by the writer show that in the artesian well at the Atlantic City water-works, cited above, after pumping ceased the water-level rose for at least three months under conditions that apparently excluded any other cause except normal recovery [5]. Furthermore, throughout the Atlantic City Region there was observed evidence of widespread lag in movement of the artesian head in response to seasonal fluctuations. A continuation of these studies by H. C. Barksdale [6] has shown that this regional lag may be of longer duration than originally supposed. So far as the writer is aware, definite studies of this phenomenon have been made only in the Atlantic City Region, although lag in response to changes in rate of pumpage has been suggested to explain the long continued drop in head--in progress for many years--in the great Dakota Artesian Basin.

A problem on which there is not much information relates to the nature of fluctuations of head in the border-zone between water-table and artesian conditions. This problem has come up especially in the Grand Prairie Region, Arkansas, where before pumping for irrigation began about 1910 the water was apparently under artesian head, but in parts of the area the head has dropped until it is below the bottom of the confining bed, part of the water-bearing formation has been drained, and a water-table now exists. If the differences in the effect of pumping from artesian and non-artesian beds are as suggested above, it would seem that under the original artesian conditions the loss of head when pumping a given quantity of water was probably transmitted more quickly to a given distance from the pumping well, and measurable effects were felt to a greater distance than under present conditions in some localities where drainage of the upper part of the formation has occurred. On the other hand, where drainage has occurred and a water-table exists, it is probable that the yield of the wells has decreased considerably as compared to the yield of wells where artesian conditions still exist. The question may be raised as to whether a sharp change in effects of pumping may be noticed in the border-zone between the two areas. These questions deserve consideration in connection with the problem of the future usefulness of wells in different parts of the Grand Prairie Region and doubtless in other regions.

Earlier investigators recognized a variety of other fluctuations besides those described above [7], and recent studies have added considerably to our knowledge of such fluctuations. Some of these fluctuations are largely only of casual interest such as those due to the passage of trains and to earthquakes. In this group also should be included the peculiar phenomenon, first observed by the writer in the well-field of the Atlantic City Water Department, of the water-level in a well penetrating one formation moving in the opposite direction to that in a well in another formation separated by thick clay beds, when pumping of the latter begins or ceases (illustrations of these fluctuations and discussion of their cause are given by H. C. Barksdale in [6]). This type of fluctuation has since been observed by the writer in two widely separated localities on Long Island. The three types of fluctuations just mentioned are generally insignificant in amount, but nevertheless they are valuable in throwing light on such problems as the elasticity and compressibility of aquifers and the transmission of artesian pressure.

Other incidental fluctuations must be recognized and understood in order that correction may be made in studying the fluctuations due to precipitation and pumping. These include fluctuations due to ocean-tides, changes in atmospheric pressure, and possibly to changes in stages of lakes and rivers. The attention that must be given to fluctuations of secondary nature varies with the amount of fluctuation and the problems under consideration. In wells in different parts of the Atlantic City Region, for example, the fluctuation due to tides ranges from a few inches to several feet. To correctly interpret the record from some wells, daily corrections are made by taking the average of the highest and lowest level reached at times of the high and low tides. Barometric fluctuations in many wells may be neglected. However, in the Grand Prairie Region, Arkansas, the amount of barometric fluctuation, as much as a foot within a week or ten days, is within the range of change in level from corresponding dates in one year to the next year. Obviously, in this region annual measurements must be adjusted for barometric fluctuations if they are to be interpreted correctly.

In many areas, fluctuations of the water-table due to transpiration and evaporation by plants are so small that they may be considered to be of only secondary importance. However, as shown by Smith [8] and White [9] in other areas these fluctuations offer a useful means of estimating discharge of ground-water by transpiration and evaporation. Troxell has recently contributed further to the study of these fluctuations (see paper in present Transactions).

Consideration of the influence of geologic factors on fluctuations of the water-table or artesian head cannot be overlooked. The geologic factors are primarily those of structure and those that affect permeability. In many regions the structure is so uniform over large areas that it need be given only passing consideration. In some areas, however, the structure will considerably affect the fluctuations. The well-field of the City of Garfield near East Patterson, New Jersey, is developed in alternating beds of Triassic shale and sandstone which dip westward with a fairly steep angle. Heavy pumping of industrial wells of about the same depth, with a fluctuation of about 50 feet in water-level in the industrial well-field, produces no observable effect on the City of Garfield wells, about half a mile distant, because with the relatively steep dip of beds the wells in the two localities are drawing on different aquifers separated by considerable thickness of relatively impervious aquifers. As another example, it is to be expected that loss of head at given distances from pumping wells in narrow alluvium filling narrow valleys cut in impervious bed-rock, where the water can move to a pumping well practically only in a downstream direction through a small cross-section, will be greater than in other alluvial deposits of equal permeability but of wide areal extent where the water can move radially to a pumping well.

The factor of permeability, although generally recognized by hydrologists in considering problems of yield of pumping wells, apparently has not been given sufficient consideration in some regions and has led to erroneous interpretation of the effects of fluctuations in precipitation. During the recent droughts, instances were reported of water being found--much to the surprise of the owners--in wells which had been abandoned months or years before because they "went dry" and supposedly had remained dry. The rather obvious explanation is that in poorly permeable material, such as loess, silt, and clay, the removal of the small quantity of water needed for domestic use may create a cone of depression with dimensions comparable to those of a cone of depression developed by pumping a much larger quantity of water from a well in more permeable material; but when the well is abandoned the water-level slowly but surely returns to or nearly to its original level, depending upon temporary conditions of rainfall. The facts just cited emphasize the necessity of having observation-wells where they cannot be affected even by the withdrawal of small quantities of water for domestic use if we are to get correct information on the effects of drought and flood and of artificial disturbances of ground-water conditions by works of man.

The present symposium has been developed primarily upon two lines, namely, long-time records of fluctuations, and shorter continuous records, so far as available, in certain areas which have recently suffered from drought, but for which long records are not available. The long-time records are valuable as guides in interpreting the short records. An effort has been made to select records from areas showing a wide variety of geographic distribution. Among the records presented is one of a well in New Jersey continuous since 1891 and one of a well in southern California continuous since 1892. So far as the writer knows, these are the longest continuous records of fluctuations of the ground-water level in the United States. The record of wells in Michigan from 1880 to 1908 (presented by R. E. Horton), although covering a shorter period, is, so far as known, the earliest record of any considerable length. Many of the areas for which records are presented have been visited by severe drought, some in early years from which they definitely recovered; others so recently that full recovery may not yet be evident. The writer will be glad to hear of other records for it is his belief that all reliable records, both long and short, should be available for study and particularly that they be preserved where they will be available in the future.

The papers of the Symposium emphasize several facts. First is the complexity of, and difference in range of, the movement of ground-water level in different parts of the country. These factors would be emphasized even more if some of the papers discussed in detail the short-period fluctuations, daily or weekly, that do not show up in the more generalized long-time curves. Second, most of the observation-wells, whether in artesian or water-table aquifers, reveal definite seasonal cycles, but these are sometimes interrupted by unusual conditions. Third, in some areas there has been notable decline of the water-level or of artesian head, but these are generally areas in which there is heavy artificial withdrawal of water, at least in comparison to the precipitation of the region or transmission- or storage-capacity of the aquifers. On the contrary, in other regions, even in spite of heavy withdrawals, there has been no notable decline in water-level or artesian head, and in view of this evidence broad statements that there has been a universal decline are not warranted. Finally, in order to get a true picture of the fluctuations of the ground-water level or head in a given locality the observations must be sufficiently detailed and cover a long enough time to show the magnitude of possible fluctuation during the daily, annual, and longer secular cycle in order to discover what fluctuations are significant and what are less significant but for which correction must be made in interpreting the records.

The writer has been studying fluctuations of the water-table and artesian head more or less intensively for the last 13 years, and more casually for several years longer, in many areas and under a considerable variety of geologic conditions. One particular impression gained by him is that new problems have been found and new information has been obtained on this subject in almost every region studied. Also more and more is he impressed with the fact that only as we obtain carefully controlled actual measurements of water-level or head in numerous scattered observation-wells in well-chosen localities, and study these scientifically, can we correctly interpret the effects of fluctuations of precipitation and of pumping and other artificial disturbances of ground-water conditions. There is plenty of evidence that hearsay information from well-drillers, owners, and others without careful periodic measurement and written records, cannot be relied upon. It is further the opinion of the writer, known to be shared by some of his colleagues but admittedly not by others, that the greatest opportunity to obtain the necessary information is a more common use of water-stage recorders. He believes also that the time has arrived when it must be recognized that this information is of sufficient value that, wherever necessary, funds must be provided for the proper construction of wells in carefully selected localities to be used for the sole purpose of observations of fluctuations of the water-table and of artesian head.

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U. S. Geological Survey,
Washington, D. C.

LONG-TIME RECORDS OF GROUND-WATER LEVELS ON LONG ISLAND, NEW YORK

R. M. Leggette

(Published with the approval of the Director, U. S. Geological Survey)

As early at 1851 the need for information as to the position of the water-table was recognized by workers on Long Island. In that year water-level measurements were made in about 32 domestic wells in the southern part of Kings and Queens counties, New York (W. J. McAlpine, Report made to the water committee of the common council of the City of Brooklyn on supplying the City with water, p. 113, Brooklyn, I. Van Anden, 1852). Although specific water-level data are given in this report, it has not been possible to determine the exact locations of the old wells that were measured, or the months during which measurements were made.

In a report by J. P. Kirkwood (The Brooklyn water-works and sewers, plate 59, Brooklyn, D. Van Nostrand, 1867) published in 1867 is a map showing contours on the water-table in the area between Jamaica, New York, and Hempstead, New York. The map is not dated, but a statement on page 59 of the report implies that the water-level measurements on which the map is based were made in the late fall of 1859 or early spring of 1860.

In 1903 the New York City Department of Water Supply, Gas, and Electricity began measurements of ground-water level in a number of test-wells in Queens, Nassau, and Suffolk counties, New York. These measurements were continued at irregular intervals until 1918, although most of the records cover only a part of this period. In 1931 the City again began periodic measurements in some of these old test-wells and in 1932 the United States Geological Survey started periodic measurements in some of the same test-wells. In the earlier years measurements were made about weekly, but in recent years they have been made only about monthly. It is to be regretted that no measurements of water-level in these test-wells were made between 1918 and 1931.

There are many factors that produce fluctuations of ground-water levels on Long Island. One of the major factors is the variation of precipitation from year to year. Figure 1 is a graph showing the cumulative departure from average annual precipitation at New York City, New York, from 1826 to 1935. From 1865 to 1935, this record was not made on Long Island, but for general comparison it is believed to be satisfactory. It is apparent from this Figure that the water-level measurements made in 1851 were obtained after a long period of subnormal precipitation. It is therefore not surprising to find that the ground-water levels during that year were lower than any time on record. Although a comparison of the available data in 1851 and 1859-60 is not as distinct as desirable, it is fairly evident that ground-water levels were somewhat lower in 1851.

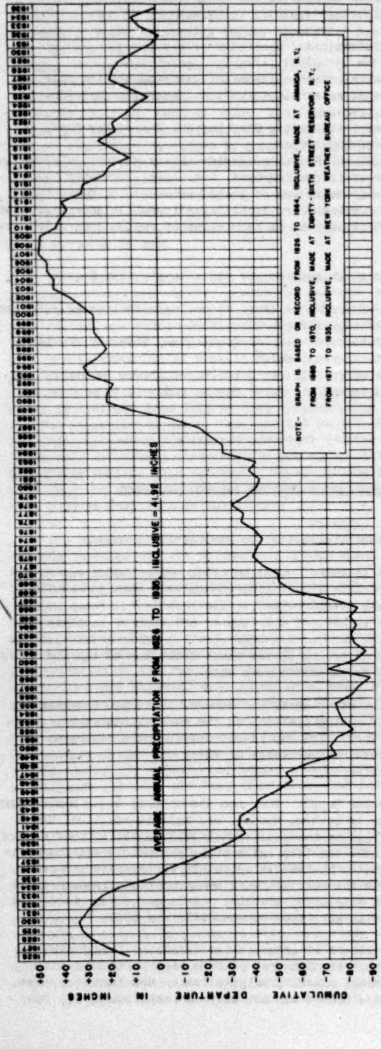


FIGURE 1—CUMULATIVE DEPARTURE FROM AVERAGE ANNUAL PRECIPITATION AT NEW YORK CITY, N.Y.

Lake Ronkonkoma, with an area of more than one-third square mile, is located about in the center of Long Island. The bottom of the Lake is considerably below the water-table in the immediate vicinity, and in a general way the Lake level fluctuates with the water-table. According to statements made by local residents in 1903, the Lake was low in 1857 and from 1880 to 1885 (W. H. Burr, Rudolph Hering, and J. R. Freeman, Report of the Commission on Additional Water Supply for the City of New York, pp. 817-818, New York, Martin B. Brown Co., 1904). From 1898 to 1903 the Lake level was rising. It was high in 1891. These statements show in a general way that the level of the Lake and therefore the water-table fluctuates with major trends of precipitation (see Fig. 1).

As is apparent from Figure 1, the ground-water-level measurements made since 1903 cover a period when the cumulative departure from average precipitation was above normal. It is to be expected, therefore, that ground-water levels would be higher than in earlier years when there was a large accumulated deficiency of precipitation. In 1859-60 they were about five feet lower than in 1903 (W. H. Burr, Rudolph Hering, and J. R. Freeman, op. cit., p. 821) and apparently still somewhat lower in 1851.

Figure 2 shows the water-level fluctuations in three of the old New York City test-wells and, for the purpose of comparison, the last 33 years of the graph shown in Figure 1. Since 1907 the graph of cumulative departure has a downward trend with its lowest point in 1932. A careful study of Figure 2 shows that the major trends of ground-water-level fluctuation follow the trends of the cumulative-departure graph. It is of interest to note that the above normal precipitation in 1933 and 1934 produced a considerable rise of the water-table, particularly in wells M-183 and Ch-201. The same effect was probably produced in 1919-20 and 1926-27, although no ground-water-level records are available for these years.

Figure 2 also shows the average daily withdrawal of water for public supply from the post-Jameco beds (shallow beds) in Nassau County, New York. Large quantities of water are withdrawn from the shallow beds at the Wantagh and Massapequa infiltration-galleries operated by New York City. Well S-45 is located only about one-half mile from these infiltration-galleries. It is apparent from Figure 2 that the highest water-level in this well in 1935 was only slightly lower than the highest water-level shown in 1903. Thus, in spite of the large quantity of water withdrawn during this period, there has been no progressive decline of the water-table, and water-levels are apparently considerably higher than in 1851 and 1859-60 when there was no large withdrawal from the shallow beds. Moreover, the period from 1903 to date was a period during which the precipitation was in general below normal. However, since 1916 the withdrawals have been considerably

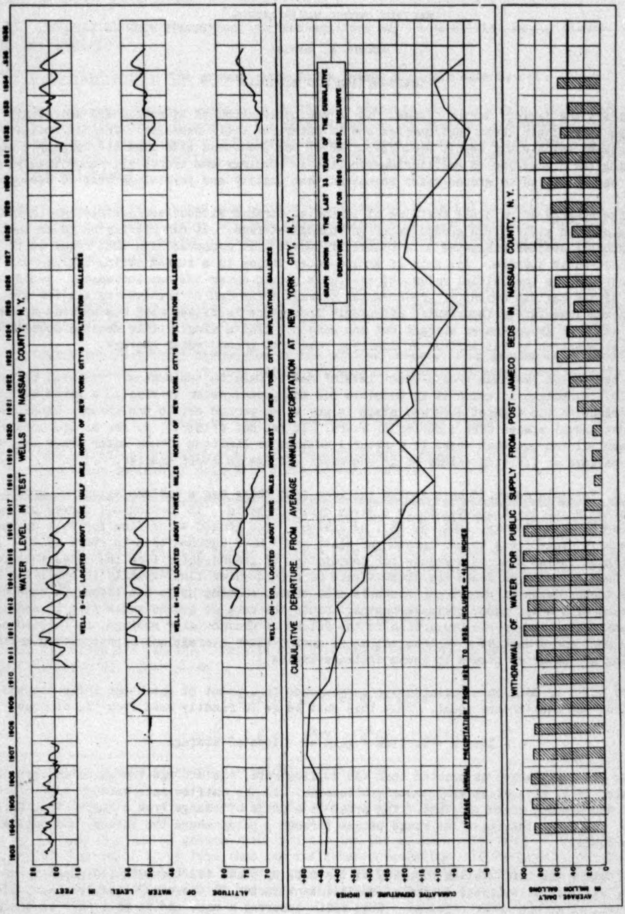


FIGURE 2 - GRAPHS SHOWING FLUCTUATIONS OF GROUND WATER LEVEL, CUMULATIVE DEPARTURE FROM AVERAGE PRECIPITATION, AND WITHDRAWAL OF WATER FROM POST-JAMECO BEDS ON LONG ISLAND, N.Y.

smaller than in earlier years and this may have resulted in somewhat higher ground-water levels since that year, but the major trends of ground-water level apparently are produced by variations in precipitation. It is apparent, therefore, that the safe yield has not been exceeded in this area. This is in contrast to conditions in the west end of Long Island (Brooklyn) where ground-water levels are at present more than 40 feet lower than in 1903 (W. F. Laase, Subsurface water-supply of western Long Island and its utilization, Munic. Eng. J., first quarterly issue, 1934, map p. 24, profiles p. 26, and recent observations by U. S. Geological Survey).

U. S. Geological Survey,
Jamaica, New York

MAXIMUM GROUND-WATER LEVELS

Robert E. Horton

Introduction and synopsis

Aquifers are living, moving things. It is the application of hydraulic and hydrologic principles to geologic facts that enables one to interpret their behavior. The difficulties of this treatment which would result from variation of the phenomena with time are largely avoided by limiting the discussion to equilibrium-conditions. Geology and hydrology, respectively, bear much the same relation to ground-water phenomena that anatomy and physiology bear to biology.

In the absence of rainfall the flow of perennial streams without surface-storage in their basins is derived either from ground-water or channel-storage. It can readily be shown that channel-storage becomes exhausted in a relatively short time compared with that required to exhaust ground-water storage. The rate of ground-water inflow to a stream during a given dry period increases as the initial volume of available ground-water storage increases. Hence the question of the maximum amount of ground-water storage which can be retained by a given drainage-basin becomes immediately important. Hydrologic literature is filled with discussions of the economic value of ground-water storage but one does not find a single title dealing specifically with the question of the maximum or limiting volume of ground-water storage.

The expression "maximum ground-water levels" may be used in two senses: (1) With reference to the limiting height to which it is possible for the ground-water to rise in a given well; (2) with reference to the highest observed stage in any given period or, in the generic sense, to the highest annual stages over a series of years. It has not hitherto, so far as the author is aware, been pointed out that there is a natural maximum or limiting ground-water stage and, _pari passu_, a maximum or limiting volume of ground-water storage in every aquifer.

[C. C. Vermeule seems to have sensed the idea that there was a maximum volume of ground-water storage which could accumulate in a given drainage-basin. In "Geological survey of New Jersey" (v. 3, Water Supply, 1894, p. 83), he states: "The ground-water flow for full ground-water seems to range close to two inches per month and I have assumed this in every case." An examination of curves used by Vermeule for computation of ground-water flow indicates that for Atlantic Coast streams he found the highest rate of ground-water flow--usually in April--to be about two inches depth of runoff per month in most cases, running up to 2.5 inches in case of some streams with deep, sandy drainage-basins. Since the rate of ground-water flow is nearly--and in many cases exactly--in proportion to the volume of ground-water storage, it follows necessarily that there must be a maximum volume of ground-water storage and corresponding maximum or limiting ground-water stages in these drainage-basins.]

Every crest or peak on a phreatograph corresponds to a point at which the inflow to and outflow from the aquifer are equal. That this must be so is readily seen from the storage-equation

$$\text{Inflow} = \text{outflow} + \text{gain or} - \text{loss of storage}$$

As long as the inflow-rate is greater than the outflow-rate, the storage increases and the ground-water level at a given well continues to rise. If the outflow-rate exceeds the inflow-rate, the storage and stage decrease. The crest is a point of change from a rising to a falling stage. Hence at the crest the stage passes through a point where the inflow- and outflow-rates are equal.

Designating the infiltration-capacity of the soil by f and the transmission-capacity of the aquifer by K_t, the ratio (f/K_t) enters as an important factor in the analytical treatment of a great variety of ground-water problems. This ratio deserves a name and it will here be designated the "transmission-ratio," since it is the ratio of the rate at which water can enter or be transmitted into the soil from rain or melting snow, to the rate at which it can flow out of the soil under unit-head.

Since the infiltration-capacity limits the rate of inflow, the limiting,maximum ground-water stage will be attained if and only if the ground-water has risen to such a stage that the ground-water outflow-rate equals the infiltration-capacity. As subsequently shown, this stage may never be reached in a given well or aquifer because rain-intensities exceeding infiltration-capacity are seldom of sufficient duration to bring the outflow-rate up to equality with f. In such cases a maximum stage or crest-stage occurs, less than the limiting stage. In such cases the crest-stage occurs when rain ends or when the rain-intensity falls below the infiltration-rate; the majority of ground-water crests are of this type.

For purposes of this discussion, surface-aquifers may be classified as (a) simple, (b) multiple, (c) compound.

In a "simple" aquifer the ground-water flows toward a single main outlet.

In many drainage-basins, especially in regions overlain with permeable glacial deposits, ground-water is continuous everywhere but each stream-valley receives ground-water from different slopes. There are no impervious divides between these sub-aquifers and such a system may be described as a "multiple" aquifer. The simple aquifers which make up a multiple aquifer may be called "sub-aquifers."

The flood-plain of a stream may contain an aquifer which is fed in part by direct infiltration and in part by ground-water drainage from adjacent hill-slope aquifers. This may be described as a "compound" aquifer. Pomperaug Valley, Connecticut, affords an excellent illustration of a compound aquifer.

While much of the discussion applies to other conditions, the treatment of this subject is primarily intended to apply to (a) surface or non-artesian aquifers, (b) aquifers in continuous porous media--not to aquifers in rock-fissures.

Following the analytical discussion of the subject, several long ground-water records are presented and examined to see if they afford evidence of behavior in accordance with the principles outlined.

Theory of limiting maximum ground-water stages

For the purpose of discussion of limiting ground-water stages, the case of a simple aquifer with an impervious horizontal sole will first be considered.

Let α be the rate of ground-water accretion, f the infiltration-capacity, and K_t the transmission-capacity of the soil, all in the same units, and with other notation as shown on Figure 1. Then for a strip of unit-width running from the stream or outlet to the phreatic divide, and for equilibrium-conditions, the inflow upstream from any point x must equal the flow past x or, measuring inflow and outflow both in terms of depth per unit of time on the entire phreatic drainage-area

$$\alpha[(\ell_o - x)/\ell_o] = K_t(h/\ell_o)S \tag{1}$$

But the slope S = (dh/dx). This is positive since the slope is upward in the direction in which x is measured. This gives

$$(\alpha/K_t)(\ell_o - x)\,dx = h\,dh \tag{2}$$

and

$$(\alpha/K_t)(\ell_o x - x^2/2) = h^2/2 + \text{constant} \tag{3}$$

where $x = 0$, $h = h_o$ and constant $= -(h_o^2/2)$. This gives

$$h = \sqrt{h_o^2 + 2(\alpha/K_t)(\ell_o x - x^2/2)} \tag{4}$$

This is the equation of the ground-water profile for the assumed conditions with any rate of accretion α either equal to or less than the infiltration-capacity. [This equation is general and applies also where α is negative or where there is uniform abstraction of water from the water-table by vegetation. The equation has many applications which will not be discussed here.]

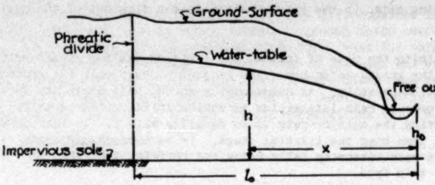


FIG. 1 - PROFILE OF SUB-AQUIFER WITH HORIZONTAL SOLE

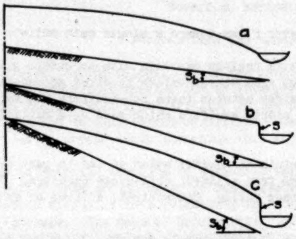


FIG. 2 - GROUND-WATER EQUILIBRIUM-PROFILES, INCLINED AQUIFERS (SCHEMATIC)
(a) $S_b < 2\sqrt{\frac{f}{K_t}}$ (b) $S_b = 2\sqrt{\frac{f}{K_t}}$ (c) $S_b => 2\sqrt{\frac{f}{K_t}}$
Cases (b) and (c) are shown with vertical seep-face S at the outlet

Let h_g be the limiting maximum stage for a given infiltration-capacity f. Then

$$h_g = \sqrt{h_o^2 + 2(f/K_t)(\ell_o x - x^2/2)} \quad (5)$$

This is the equation of a parabola with the vertex at the point p, Figure 1, that is, at the intersection of the water-table and the phreatic divide.

It has been noticed that the profiles of surface-aquifers such, for example, as those between tile-drains, are not always precisely parabolic. One reason is that they are not taken under equilibrium-conditions. Since ground-water rises as long as inflow exceeds outflow, and falls whenever outflow exceeds inflow, it follows that at every maximum point on a phreatograph a condition exists temporarily where inflow and outflow are equal, that is, an equilibrium-condition, for which the formula applies.

Effect of various factors on limiting maximum ground-water stages

Tne manner in which the limiting maximum stage is affected by changes in the controlling variables is most easily seen by converting formula (5) into an expression for extreme range of ground-water fluctuation. Since the outlet level h_o represents the minimum possible stage where there is only a single outlet, it follows that

$$\text{Range} = h_g - h_o = \sqrt{h_o^2 + (f/K_t)(2\ell_o x - x^2)} - h_o \quad (6)$$

The equation was derived with reference to a strip of unit-width and hence applies strictly only to an aquifer having a rectangular catchment-area. Catchment-areas of simple aquifers are as varied in form as those of topographic drainage-basins, which they generally resemble.

If w_a is the average width of the phreatic drainage-basin upstream from a given point x, and w its width at x, then the flow past x bears the ratio (w_a/w) to that which would result for a rectangular phreatic basin of width w. It can readily be seen that for an irregular-shaped phreatic basin the flow past any point x is the same as it would be for a rectangular basin of width w but with an infiltration-capacity $(w_a/w)f$ instead of f. Making this correction, equations (5) and (6) can be written in the form

$$h_g = \sqrt{h_o^2 + (w_a/w)(f/K_t)(2\ell_o x - x^2)} \quad (7)$$

and

$$\text{Range} = \sqrt{(w_a/w)(f/K_t)}\ \sqrt{2\ell_o x - x^2} \quad (8)$$

Equation (8) shows that, other things equal:

(1) The limiting stage and range of fluctuation at a given well vary in proportion to the square root of the width-ratio and also in proportion to the square root of the transmission-ratio. If either ratio is doubled, the limiting stage and range are increased 41 per cent. If halved, the stage and range are decreased 29 per cent. If both are doubled, the range is doubled. If both are halved, the range is halved, and if one is doubled and the other halved, there is no change in the range or maximum stage.

(2) For a well at a fixed distance from a stream or outlet, the range and limiting stage increase with the length ℓ_o or the length of underground flow of the water approaching the well.

The relative values of the range for different ratios ℓ_0 to x, computed by formula (8), are as follows:

ℓ_0/x =	1	2	3	4	5	6	7	8	9	10
Range =	1.0	1.73	2.24	2.64	3.00	3.16	3.60	3.87	4.12	4.36

Wells at a given distance from the outlet in a long narrow aquifer have correspondingly larger ranges and higher maximum stages than similar wells in a shorter, wider aquifer of equal surface area.

(3) For an aquifer of a given length ℓ_0, the range and limiting stage increase with the distance of the well from the outlet or with the ratio (x/ℓ_0) as follows:

x/ℓ_0 =	0.0	0.1	0.2	0.4	0.6	0.8	1.0
Range =	0.0	0.19	0.36	0.64	0.84	0.96	1.0

For wells near the outlet the range increases rapidly with distance from the outlet. For wells near the phreatic divide, increase of range with distance from the outlet is relatively small.

Stratification

In this connection, stratification of an aquifer may be considered as any degree or arrangement of horizontal variations or diversity in the water-bearing medium which affects the hydraulic conditions. In addition to true stratification, this includes the important case of gradual variation, usually a decrease in such factors as porosity and transmission-constant proceeding downward from the surface. Extensive areas of Hudson River shale in eastern and central New York afford an excellent example. This rock weathers rapidly when exposed to the air or frost, but at a slight depth below surface it is wholly impervious. There is water in the fractured surface, decreasing in amount until at a depth, usually of a few feet, no water is found. Similar conditions exist in other classes of rocks and soils.

Let K_1 be the transmission-capacity of the aquifer at a height of one foot above the impervious level. Then at a height h the transmission-capacity is K_1h and the average below the height h is $K_1h/2$.

Considering a horizontal surface with the origin at the impervious level and at the outlet-end of the aquifer, then for equilibrium of inflow and outflow

$$(\ell_0 - x)\, f = (K_1h^2/2)\,(dh/dx)$$

Integration gives

$$(2f/K_1)\,(\ell_0 x - x^2/2) = h^3/3 + \text{constant} \qquad (9)$$

When $x = 0$, $h = h_0$, therefore constant $= -\,h_0^3/3$. Inserting $(w_a/w)f$ in place of f to allow for form of the aquifer, the equation for the maximum limiting stage becomes

$$h_g = \sqrt[3]{h_0^3 + 3(w_a f/wK_1)\,(2\,\ell_0 x - x^2)} \qquad (10)$$

This is the equation of a parabola of two-thirds power. The profile-equation in other respects is identical with that of a homogeneous aquifer. The discussion of limiting ground-water stages and range, based on the equation for homogeneous aquifers, is therefore applicable to stratified aquifers of this type except that the maximum stages will not be the same in the two cases. It is also possible to obtain an equation for limiting stage applicable to an aquifer consisting of two or more horizontal strata with fixed lines of demarcation between them. Because of the great variety of conditions which this situation presents, it will not be discussed here.

Aquifers with inclined soles

The differential equation of the equilibrium-profile for an aquifer with inclined sole, typical of many hillside aquifers, is easily stated and has been integrated and studied at the Horton Hydrologic Laboratory. The resulting profile-equation is complicated and does not as readily show the effect of changes in individual factors as that given above. The profile-equation for horizontal aquifers has therefore been used for purposes of discussion.

While the conditions which fix limiting stages of hill-slope aquifers are essentially the same as for aquifers with horizontal soles, there are certain important differences. For horizontal aquifers both the limiting stage and the range increase proceeding upstream from the outlet. For sloping aquifers there are three principal cases and several sub-cases, dependent on the relations between the variables. The principal cases are outlined in Figure 2.

(1) Slope of sole $S_b < 2\sqrt{f/K_t}$--Underground back-water extends from the outlet to the divide and the depth at the divide is not zero. The maximum stage increases but the range generally decreases proceeding upstream from the outlet.

(2) Transition-stage, slope $S_b = 2\sqrt{f/K_t}$--It can readily be seen that for an aquifer with a sloping sole and uniform infiltration-rate, there is a certain constant slope for which the inflow upstream from a given well will equal the flow past the well. The profile of the water-table is nearly a straight line, extending from the sole at the divide to the outlet or to a minimum level adjacent to the outlet. In this case the limiting ground-water stage increases and the range decreases, both uniformly, proceeding upstream.

(3) Steep aquifers, slope $S_b > 2\sqrt{f/K_t}$--The depth at the divide is zero, and for a constant level at the outlet the stage increases proceeding upstream. The range is zero at the outlet and also at the divide and has a maximum at some intermediate point.

In some of these cases there is a minimum level at which the ground-water flow can arrive at the outlet. If the actual water-level in the outlet channel is below this minimum, there will be a "seep-surface" at the outlet, that is, ground-water will enter the stream at a level above the stream-level.

Surface and gully-outlets, bornes

In addition to the geologic and physical factors which fix the limiting ground-water stage in a given aquifer or well, there are certain topographic conditions to be considered. So far it has been assumed that the aquifer has only one outlet. Theoretically the water-table in an aquifer with a horizontal sole would intersect the ground-water if the aquifer extended back far enough from the outlet. For aquifers with inclined soles there are cases of this kind and also cases where the water-table would never intersect the ground-surface.

Swamp aquifers--In case of many swampy areas or in case of undissected flat or sloping areas with impervious floors at a slight distance below the surface, conditions of equilibrium may lead to a limiting ground-water stage h_g above the level of the soil-surface over part of the tributary area. On such areas the soil may be continually flooded or the ground-water may rise to the surface only at times. Swampy areas with deep muck-deposits underlain by impervious beds, such as the Everglades of Florida, provide excellent examples of aquifers of this type. As long as the surface is flooded, infiltration takes place at a constant rate equal to the infiltration-capacity and there is flow of ground-water to the outlet at the same constant rate. Rain tends to produce surface-runoff at an intensity approaching the rain-intensity as a limit, since in this case the ground-water outflow equals the infiltration-rate. Large reduction of runoff-intensity below rain-intensity is, however, usually provided by surface-storage. In case of swamp aquifers the maximum limiting stage is, of course, the ground-surface.

Ephemeral outlets, bournes--If the surface of the terrain is serrated by gullies, shallow relative to the main outlet of the aquifer, the conditions may be such that before reaching the limiting stage the water-table will begin to intersect the gullies. These will provide ephemeral or auxiliary outlets for ground-water. In general, the ground-water above the level of the bottom of the gully will flow a distance equal to one-half the spacing between gullies to reach an outlet. The great reduction in length of underground flow as compared with that required to reach the main outlet will limit the maximum ground-water stage to a height a little above that of the gullies. Conditions of this kind are fairly extensive. They are of particular interest because of the state of affairs to which they give rise in connection with flood-runoff. Until the water-table reaches the level of the auxiliary outlet, rain, however intense, cannot produce a surface runoff-rate exceeding the difference between the rain-intensity and infiltration-capacity. Rainfall not exceeding the infiltration-capacity, however prolonged, will therefore produce no surface-runoff. After the water-table rises to a point where gullies are intersected, and the limiting ground-water stage is attained, ground-water outflow-rate will equal the infiltration-capacity and, except for surface-storage, the runoff-intensity from then on will equal the rain-intensity. Thus it may happen that long-continued rains will produce little or no surface-runoff and no increase in ground-water flow until the field-moisture-deficiency becomes zero; then, somewhat abruptly, rain of no greater intensity will produce a relatively high runoff, substantially the same as if the infiltration-rate had been reduced to zero. Such high runoff-intensities are commonly but inaccurately ascribed to the "soil becoming saturated." Actually the soil is not saturated above the water-table but the ground-water inflow and outflow have become equal, so that the total runoff-intensity approaches the rain-intensity as a limit.

If it happens that the water-table intersects gullies when the water-level is considerably below its limiting stage, the condition known in the chalk-downs of England as a bourne may result. A bourne is a stream fed by ground-water where the head of the stream or source of the flow travels up and down the stream-valley with the fluctuations of ground-water level. I have noticed this condition in certain shallow stream-valleys on the south slope of Long Island.

Local variation of ground-water regimen

It is sometimes found that in a group of adjacent wells the phreatographs are all closely similar except that fluctuation and range of stages in some wells is greater than in others. This is commonly attributed to local differences in permeability of the material comprising the aquifer, it being assumed that the wells showing the greatest range are in the least permeable beds. It is true, as formula (8) shows, that if permeability alone varied, then, since the range varies inversely as the square root of the permeability, it would be greatest for wells supplied by the least permeable aquifers. This, I think, is not generally the correct explanation. It will be noted that the range varies as the square root of the transmission-ratio. Permeability and infiltration-capacity, though not usually identical, are closely related. They may be practically identical in sandy soils containing little colloidal material. In general, if the surface of the soil and water-bearing beds are of the same or similar material, a change in transmission-capacity is accompanied by a similar and nearly proportional change of infiltration-capacity; the transmission-ratio may be changed but little and hence the fluctuations and range for a well may not in general vary to any great extent with change of transmission-capacity of the water-bearing beds.

There are other factors quantitatively adequate to explain differences in range of adjacent wells or wells in adjacent aquifers.

Summarized briefly, the factors which fix the maximum limiting stages and range for a given well and aquifer are: (1) Length of aquifer; (2) distance from well to outlet; (3) shape, as expressed in the width-ratio (w_a/w); (4) transmission-ratio (f/K_t); (5) slope of the sole, if not horizontal; (6) homogeneity and stratification; (7) topographic controls, gully-intersections, etc.

These factors are of more or less equal importance. Differences in any one or in any combination may produce considerable variation in range of one well as compared with other adjacent wells.

The effects of the first four factors are rigorously taken into account in equation (8) for homogeneous aquifers with horizontal soles. The others can be taken into account in similar analyses.

Keeping in mind the distinction between limiting ground-water stage and other maximum or crest-stages, it will be seen that the analysis thus far given does not show if or when the limiting maximum stage will be attained.

Conditions which determine times and frequency of occurrence of limiting ground-water stages

The limiting stage may be attained at frequent intervals; for example, it may be attained, as a rule, once each year, or it may be rarely attained or never attained. The frequency with which it will be attained depends on certain factors in addition to the seven described which govern its height. These are: (1) Initial ground-water storage; (2) initial ground-water level and field-moisture-deficiency; (3) duration of rainfall-excess. Since the limiting stage can only be attained at times when there is rainfall-excess over the infiltration-capacity, the criterion which determines the minimum duration t_e of rainfall-excess which will permit the ground-water to reach the limiting stage is

$$ft_e \geqq fmd + Q_g - Q_0$$

where fmd is the field-moisture-deficiency at the beginning of any given period of rainfall-excess and Q_0 and Q_g are the volumes of ground-water storage at the beginning of rainfall-excess and at the limiting ground-water stage, respectively. It will be seen that. other things equal, rainfall-duration and, more specifically, duration of rainfall-excess, is the principal controlling factor. Ground-water maximum stages occur at all seasons of the year but in general, particularly in middle latitudes, maxima in the spring months, usually just after the frost has gone out of the ground, tend to predominate.

Using the water-year beginning March 1, the 20-year record at the farm well at the Horton Hydrologic Laboratory shows that the maximum stage has occurred: Fifty per cent of the years in the spring months, March to May; 25 per cent of the years in the winter months, December to February; 15 per cent of the years in the fall months, September to November; 10 per cent of the years in the summer months, June to August.

Records of ground-water level in the chalk-downs in Sussex, England, compiled by D. Halton Thomson, and extending back continuously to 1836, show midwinter maximum levels strongly predominating. The excellent records of the Italian Hydrometric Service show midwinter maximum ground-water levels predominating at some stations, spring and early summer maxima at other stations. Several long ground-water-level records in Michigan show spring maxima strongly predominating, these usually occurring about the time the frost goes out of the ground or shortly after.

There are four factors which operate together to bring about the occurrence of ground-water maxima in the early spring: (1) Seasonal variation of rainfall-duration; (2) storage-deficiency; (3) melting of snow; (4) frost-removal. The manner in which these factors operate to produce maximum and limiting ground-water stages does not seem hitherto to have been described.

(A) Rainfall-duration--In many localities, including northern United States, rainfall-duration per shower or storm is much greater, and rain-intensity in inches per hour much less, in fall, winter, and spring than during midsummer months. Analysis of hourly rain-intensity records for ten years at representative regular United States Weather Bureau stations shows, in general, winter rainfall-duration per shower or storm one and one-half to two times as great as in summer, and summer average rain-intensity two to three times as great as for winter conditions. For a given infiltration-capacity the duration of rainfall-excess is therefore generally much greater in fall, winter, and spring than in midsummer and the chances of attainment of the limiting ground-water stage are correspondingly greater than in summer, provided the infiltration-capacity is the same. For rains sufficiently long-continued to produce limiting ground-water stages, the infiltration-capacity is usually at or near its minimum value for the given soil. If the ground is not frozen, this minimum value is nearly constant throughout the year except as it is affected by temperature. If, owing to recent cultivation of the soil, the infiltration-capacity tends to be much higher than the minimum, then the limiting stage and the volume of ground-water storage which must be replenished before the limiting stage can be reached are both increased. Nevertheless, high ground-water stages are sometimes attained in midsummer, as has happened twice at the author's well.

(B) Field-moisture-deficiency--Another reason why ground-water maxima are less frequent in summer than in early spring is because there is no abstraction of moisture from the soil by vegetation during the winter season; consequently the field-moisture-deficiency is usually less in winter than in summer--in fact, it is often relatively slight, especially if it has been replenished by fall rains. If the ground has been frozen for a long period, the ground-water storage-deficiency below the limiting level may, however, be nearly or quite as great at the end of the winter as in a summer dry-period. It appears, therefore, that as between the two factors, rainfall-duration and storage-deficiency, the former is the more important in relation to fixing the time of occurrence of ground-water maxima and limiting stages.

(C) Frost-removal--The author believes, although data for quantitative proof are not available, that an important factor in producing maximum ground-water stages in the spring is the rapid flushing of large volumes of water to the water-table when the frost goes out of the ground. This phenomenon has occasionally been noticed in connection with lysimeter-records. The author has observed two or three inches of water passing downward through a 3-foot depth lysimeter within a day or two after the frost went out of the ground.

The process involved seems to be as follows. The frost melts from the surface downward and, in the case of loams and heavier soils containing colloid material, most of the melt-water remains in the soil. It is true that, while there is usually some infiltration through frozen soils, yet, except in case of sandy soils, the infiltration-rate through frozen soil is relatively small--the rate is apparently measured in terms of thousandths rather than tenths of an inch. Expansion of ice in freezing produces a degree of porosity and a transmission-capacity at the time the frost goes out greatly in excess of the normal minimum values of these quantities. This condition persists until the soil has become settled. When the frost goes out there is in the soil a column of water representing a fraction of the volume considerably in excess of the normal gravitational voids, all of which passes immediately downward to the water-table and often produces the maximum ground-water stage of the year. Incidentally this seems to be one of those wise provisions of nature, so often observed. This same volume of water, if it entered the water-table gradually over a period of two or three weeks while the soil-frost is melting, might be drained away as fast as it entered, leaving the water-table at about the same level as at the beginning of the melting period. Instead, all this water is flushed quickly into the water-table with little loss, just before the beginning of the growing season, and therefore provides the maximum available volume of ground-water storage for the subsequent dry period.

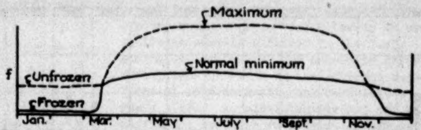


FIG. 3-SEASONAL VARIATION OF INFILTRATION-CAPACITY, MEDIUM LOAM-SOIL (SCHEMATIC)

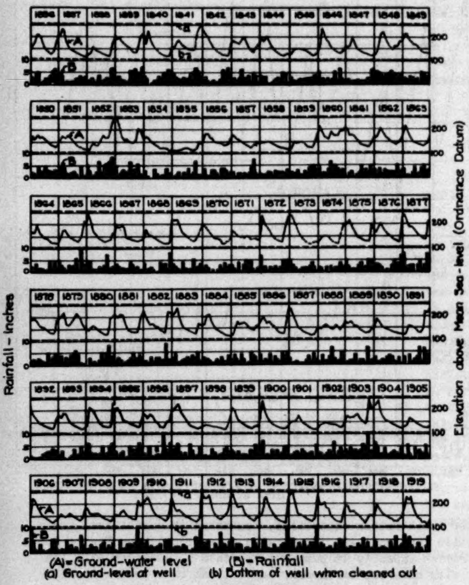


FIG. 4-RAINFALL AND GROUND-WATER LEVEL IN CHALK AT CHILGROVE, W. SUSSEX, ENGLAND
(DATA BY D. HALTON THOMSON)

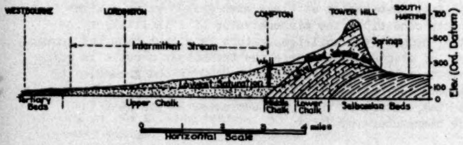


FIG. 5-GENERAL SECTION ACROSS SOUTH DOWNS ALONG COMPTON AND EMS VALLEYS
(DATA BY D. HALTON THOMSON)

(D) Snow-cover--The complex phenomena taking place in the contact-zone between the soil-surface and a layer of melting snow are of great importance hydrologically but cannot be fully discussed here. It may be noted in passing that in case of heavy soils, where the process just described takes place, water derived from melting snow may contribute largely to the volume of water flushed into the water-table when the frost goes out, thus providing a high spring ground-water level in the absence of coincident rainfall. In case of sandy soils with low field-moisture-capacity, infiltration takes place at a relatively high rate even when the ground is frozen. Melting snow may provide a continuous supply of water for absorption by the soil of much longer duration than is ever provided by rainfall alone. For sandy regions in middle latitudes the occurrence of maximum ground-water stages in the early spring is likely to be due to this cause. There is, however, a limitation to the rate at which water can be supplied to the soil by this process, since snow can only melt at a rate dependent on the temperature-excess over 32° F.

Seasonal variation of ground-water range

For loams and heavier colloidal soils there is a somewhat irregular seasonal cycle of variation of infiltration-capacity. The transmission-capacity of the underlying aquifer remains constant except as affected by the variation of ground-water temperature, which is usually small.

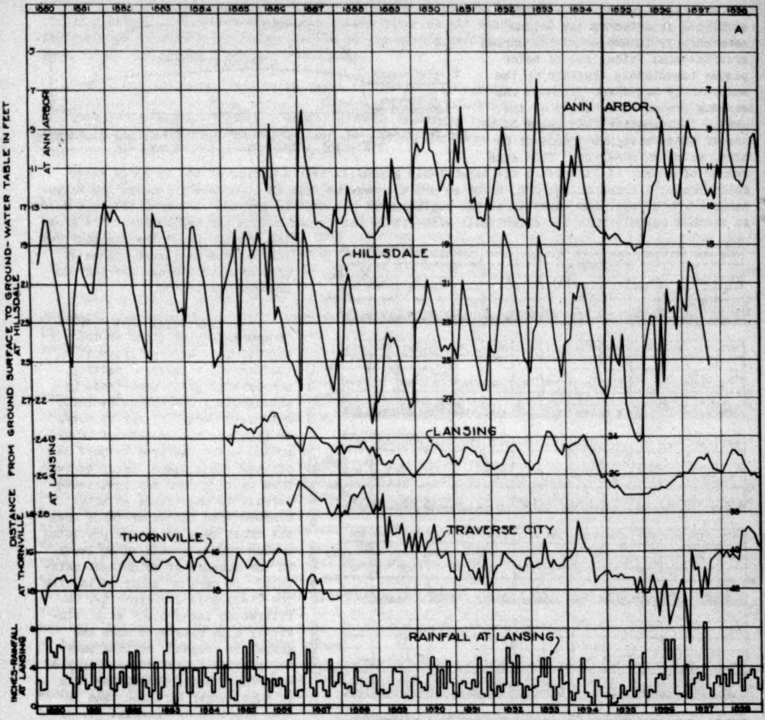
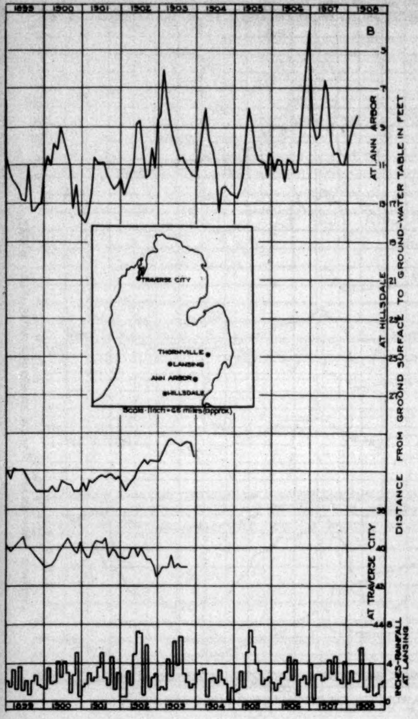


FIG.6-GROUND-WATER LEVEL RECORDS IN MICHIGAN
(DATA BY HENRY B. BAKER)

The relations of winter and summer infiltration-capacities, transmission-capacities, and transmission-ratios for a typical fertile loam soil are illustrated schematically by Figure 3. The upper of the two lines for infiltration-capacity in summer represents a condition with the soil newly cultivated, sun-checked or with numerous earthworm, insect, and root perforations. The lower line represents the minimum infiltration-capacity for a moist soil, packed by rain, and with the larger openings closed by swelling of colloids or inwashing of fine materials. The minimum infiltration-capacity seems to be nearly a constant and definite characteristic of the soil-type. Also the minimum line represents conditions usually prevailing during long-continued rains and hence corresponds to the infiltration-capacity at times when ground-water maximum stages are or may be attained. For summer conditions the minimum value of f is likely to be greater than the transmission-constant K_t because the soil-temperature is higher than the ground-water temperature. For example, in case of a sandy soil, where the transmission-ratio is unity at equal temperatures, and in a region with mean annual temperature of 50° F and ground-water temperature constant at 50° F, the transmission-ratio will be increased 15 per cent under midsummer conditions with a ground-surface temperature of 70° F and decreased 15 per cent for winter conditions with a ground-surface temperature of 32° F.

Since the transmission-ratio is usually greater in midsummer than in the remainder of the year, it is evidently possible, other things permitting, for higher ground-water stages to be attained in midsummer than in the fall, winter, or spring.



The question naturally arises: Why are the maximum ground-water levels in mid-latitudes usually attained in the early spring or late fall? The answer is derived from a consideration of the seasonal relations of rain-intensity and duration already given. A rain-intensity > f and of sufficient duration to provide ground-water equilibrium or the limiting seasonal ground-water stage may be a common occurrence in fall and spring but only a rare occurrence in midsummer. Quantitative treatment of this subject by the use of curves of rainfall-intensity versus duration for different seasons of the year can easily be carried out. Space-limitations forbid full treatment here but it is evident that, while the limiting maximum ground-water stage for spring conditions is likely to be reached in the majority of years, the higher limiting maximum stage for midsummer will be reached only at rare intervals, if ever. Figures 4, 6, 8, and 9 serve well to illustrate these conditions.

Too much precision should not be expected in relation to the limiting maximum ground-water level at a given well. Even where the well-level is independent of the outlet-level, as it usually is in case of hillside aquifers not too close to streams, and even where it is controlled solely by the minimum infiltration-capacity, there is a variation in the latter, outside the frost-season, of at least 10 to 20 per cent due to temperature and other causes. There will be a corresponding variation in the limiting maximum ground-water stage of 5 to 10 per cent. If, for example, the highest observed stage at a given well is 20 feet below ground, the aquifer is 20 feet deep and stages 18 to 20 feet occur in some years, it may be fairly assumed that any stage less than about 20 feet below ground represents the limiting maximum stage for the conditions pertaining at the time it occurs.

Ground-water levels in the chalk-downs, Sussex, England--The longest continuous ground-water-level record known to the author is that compiled and published by D. Halton Thomson for a well in the chalk at Chilgrove, West Sussex, England [The effect of rainfall on the saturation-level in the chalk at Chilgrove, West Sussex, from 1836 to 1919, British Rainfall, 1919; also Hydrological conditions in the chalk at Compton, W. Sussex, Inst. Water Eng., 1921, (second paper) 1931]. The record extends back with short intermissions to 1834 and so covers more than a century. The record to 1919 is shown graphically on Figure 4. This is an excellent example of a well which overflows at the ground-surface. It will be noted that the maximum level is very definitely fixed but is only reached in occasional years. During dry years the ground-water level may remain continuously low for several years, as in 1887-91. In order that there may be ground-water accretion, the field-moisture-deficiency must first be eliminated. In most of the years shown on Figure 4 there was some rise of the ground-water level in the spring, showing that in spite of the long-continued drought, there was no field-moisture-deficiency at the beginning of the growing season. An important point in this connection is that the effects of a prolonged drought on the ground-water supply to streams is often much more prolonged than the effect of the drought on vegetation. As a rule, accretion to the water-table occurs and there is no field-moisture-deficiency in humid climates at the beginning of the growing season in years of drought. Vegetation suffers because of subsequent deficiency in rainfall. When this

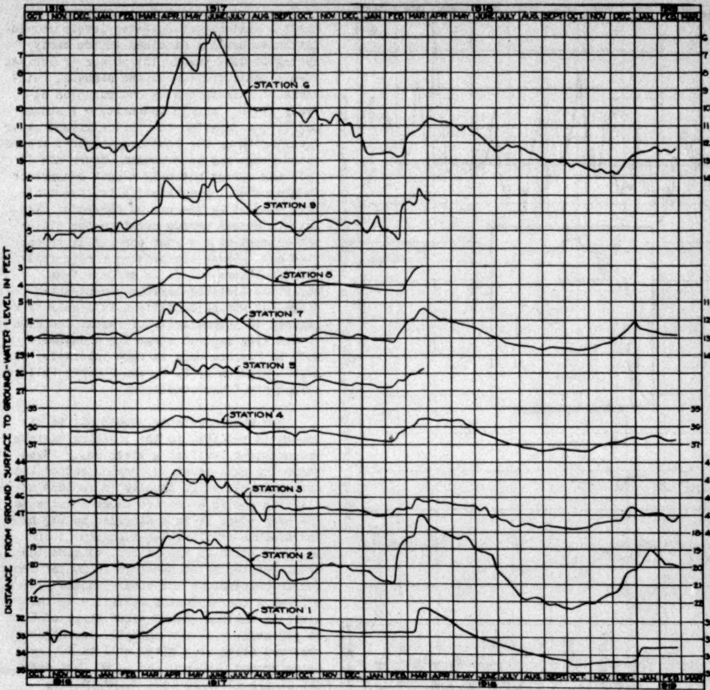


FIG. 7-GROUND-WATER LEVEL RECORDS, HURON RIVER DRAINAGE-BASIN, MICHIGAN
(DATA BY C.O.WISLER)

ends, normal soil-moisture conditions are almost invariably restored inside of a year, whereas several years may elapse before the water-table rises to its maximum or even to its normal level.

D. Halton Thomson has also kept and published an excellent record of ground-water levels in the chalk at Compton, West Sussex, beginning 1903. As large-scale phreatographs of this record have been published, it is not reproduced here. The Compton well is an excellent example of an aquifer with a bourne-outlet. Referring to the cross-section, Figure 5, it will be seen that the head of the bourne migrates throughout a range of more than four miles. This record is remarkable because of the wide range of fluctuation of the water-table. The extreme variation in height of the water-table at the Compton well is 126.2 feet. It appears that in this case the limiting stage is about 220 feet (Ordnance datum), but this stage is only attained at rare intervals.

Ground-water levels in Michigan--Dr. Henry B. Baker, long-time secretary of the State Board of Health of Michigan, believing that there was some relation between water-level in wells and the occurrence of typhoid fever of the virulent rural type, common in the middle west of his time, established well-records at several locations in southern Michigan, beginning in 1880. Some of the records were continued to 1908. Readings were taken in each well once a month, about the middle of the month. The longer and better records are shown graphically on Figure 6. In spite of the approximation due to single monthly readings, there is a close agreement between the curves for Ann Arbor and Hillsdale, although these places are 60 miles apart and in different drainage-basins. Corresponding stages are reflected, with greatly reduced range, in the records

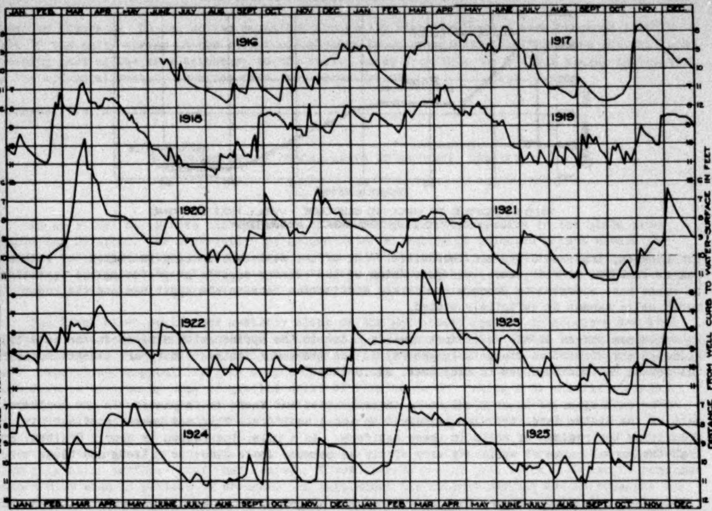
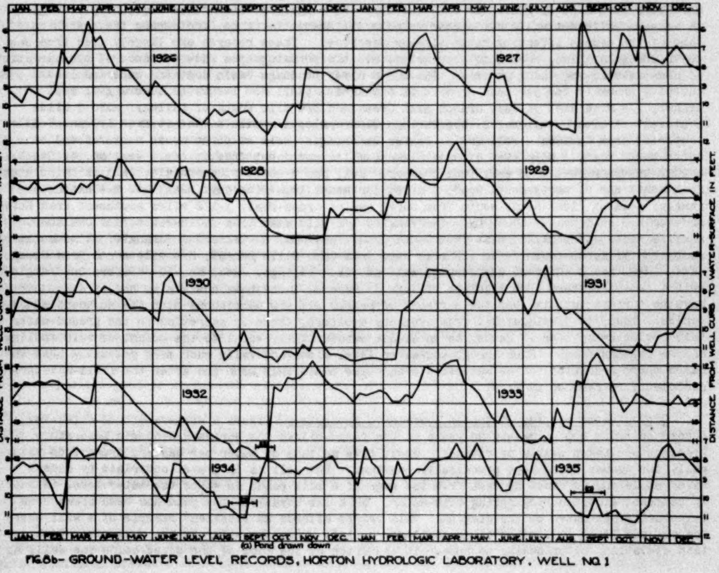


FIG.6a - GROUND-WATER LEVEL RECORDS, HORTON HYDROLOGIC LABORATORY, WELL NO 1



(a) Pond drawn down

FIG.6b - GROUND-WATER LEVEL RECORDS, HORTON HYDROLOGIC LABORATORY, WELL NO 1

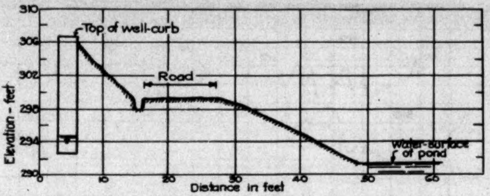


FIG.9— PROFILE OF GROUND-SURFACE ~ WELL NO.1 TO POND HORTON HYDROLOGIC LABORATORY

for Lansing, Traverse City, and Thornville. All of the wells are located in regions of rather coarse-textured glacial sands, and just which of the reasons capable of producing the variations in range have operated to produce the marked distinction between the upper two and the lower three wells cannot be definitely stated.

Maximum stages of all wells most usually occur in the spring, with minimum in the late fall, although the highest rainfall is in general in the midsummer months. There are exceptions where the annual maximum occurred in midsummer, as in 1900.

The rock floor of lower Michigan is saucer-shaped and there is in places, in the southern part of the State, large artesian leakage into local aquifers. This may have the effect of equalizing the regimen of wells in these aquifers. As a rule, the region is poorly drained, so that the normal range of wells may vary widely as between those close to outlets and those more remote.

Huron River Basin--Figure 7 shows the results of ground-water-level observations taken continuously at different stations in the Huron River Drainage-Basin in southern Michigan. The data have been furnished by Professor C. O. Wisler. Here again we find close similarity of regimen as between different wells but a considerable difference in range, indicating the operation of some of the causes affecting range already described. These records are largely free from saw-tooth irregularities, common to some wells, and the phreatographs show evidence of the operation of some natural smoothing process. The Huron River Drainage-Basin contains numerous lakes, covering probably ten per cent or more of the area. [Well No. 1--Dexter Quadrangle; well on highway 1/4 mile east of east branch Mill Creek and 3/4 mile south of railway; also 3 miles southeast of Lima. Well No. 2--Stockbridge Quadrangle; 1/2 mile northeast from Sylvan, 5 miles southwest from Chelsea. Well No. 3--Dexter Quadrangle; well at first house north of end of north-south road, 1 mile east of small lake 5 miles northwest from Dexter. Well No. 4--Stockbridge Quadrangle; 1 mile east from Gregory. Well No. 5--Dexter Quadrangle; well at third house from south end of north-south road, 2 miles northeast from Pinckney. Well No. 6--Dexter Quadrangle; well at first house south from north end of cross-road, 1-1/2 miles southwest from Horseshoe Lake. Well No. 7--South Lyon Quadrangle; 1/2 mile east from southwest corner Oakland County, 2 miles south and a little west from South Lyon. Well No. 8--Milford Quadrangle; at house at south end of north-south road, 1/2 mile east from Ohio Mills school, 3/4 mile south from Beach Lake. Well No. 9--Milford Quadrangle; well at Wixon village. Well No. 10--Milford Quadrangle; well 1-1/4 miles east from Highland village.] Some of these have outlets to the streams, others have no surface outlets, but the surfaces of nearly all are continuous with the adjacent water-tables. Thus, as distinguished from ordinary aquifers, there is accretion to the ground-water in this region every time it rains, to an extent substantially equal to the amount of rain falling on the lake-surfaces. Thus the ground-water level rises and falls much more gradually than in cases where accretion to the water-table can take place only when and after the field-moisture-deficiency is reduced to zero.

Ground-water records at Horton Hydrologic Laboratory--Figure 8 shows a ground-water-level record covering approximately 20 years at the farm well at the Horton Hydrologic Laboratory. Readings are taken weekly or oftener. About five gallons of water per day are drawn from this well, the amount being kept practically constant. The well is in gravel underlain by Hudson River shale and is about 50 feet from the edge of a mill-pond, in which the water-level is nearly constant except during spring high-water. On a few occasions the pond has been drawn down temporarily, as noted on the diagram. This record affords an excellent example of a well where the maximum level is limited by an auxiliary outlet. When the water in the well rises to a certain elevation, water begins to appear in the ditch at the foot of the slope below the well, as shown on Figure 9. On one or two occasions abnormally high levels have been recorded in this well in the early spring as the result of LaGrange Brook overflowing upstream from the well and flooding part of the area tributary to the well. Aside from this the maximum stage, as limited by the ephemeral outlet, is about five feet below ground.

Voorheesville, New York

FLUCTUATIONS IN GROUND-WATER AT WOODGATE, NEW YORK

E. S. Cullings

In an effort to improve the operation of river-regulating reservoirs in the Black River Regulating District, the observation of ground-water elevation at selected points within the District was begun in 1926, and has been continued to the present date at a limited number of stations. As yet no attempt has been made to draw conclusions, but some of the results obtained after nearly ten years of observation are submitted for discussion and suggestion.

The Black River drains the westerly slope of the Adirondack Plateau in northern New York and flows into Lake Ontario, draining an area of 1,918 square miles. Except in the lower reaches of the river and in the extreme westerly margin of the drainage-area, the underlying rock is a hard, impervious, crystalline rock of pre-Cambrian age, having the characteristics of granite. This rock is covered by beds of glacial drift of varying depth, dating from the Pleistocene glacial epoch. These sands provide a vast underground reservoir, or rather a system of reservoirs, covering the whole Adirondack Plateau, nearly 10,000 square miles in area.

The discharge of ground-water maintains the flow of the Adirondack streams at a relatively high rate after surface-runoff has ceased. These streams seldom fall below 0.25 sec-ft per square mile even in periods of drought. To supplement the natural storage and to equalize the flow through the year, the Black River Regulating District has in process of development a system of reservoirs, three of which have been in operation for some years. In an effort to coordinate the uncontrolled ground-storage with the regulated storage in the reservoirs, the more or less systematic observation of ground-water elevation was begun about ten years ago.

Owing to lack of funds it was impossible to put down observation-wells in the most favorable locations, from the geological point of view, and it was necessary to utilize abandoned or little-used domestic wells in the best available locations.

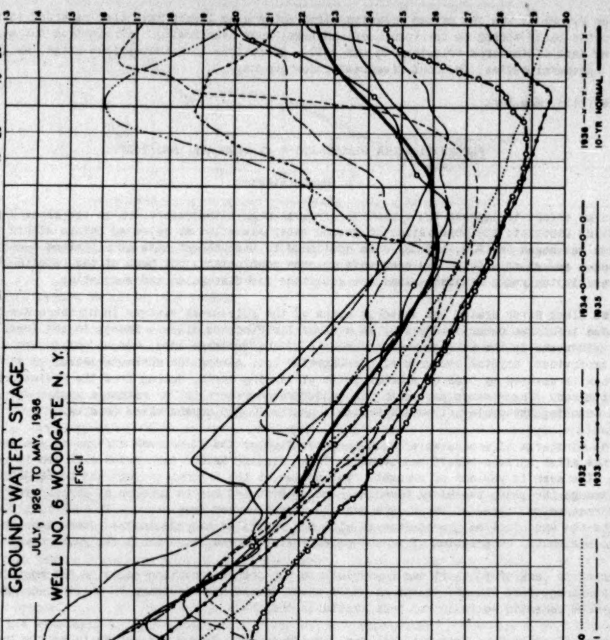
About 50 wells have been observed for periods varying from a few months to nearly ten years. Observations at most of these wells were discontinued after a few months, because for various reasons they did not yield significant results. Many of the wells appeared to be in regions of definite underground flow, and in these areas the rise and fall of the water-table does not indicate accurately the depletion and replenishment of ground storage.

Lack of funds has limited observations to occasional visits, except at one station, which seemed to offer the most satisfactory results and at which weekly observations have been made by a paid observer since 1927. The curves on Figure 1 show the rise and fall of ground-water at this station, known in our records as Well No. 6, for a period of nearly 10 years. Figure 2 is a continuous hydrograph of ground-water stage for the 10-year period. On Figure 2 is also shown the precipitation by calendar months for the same period.

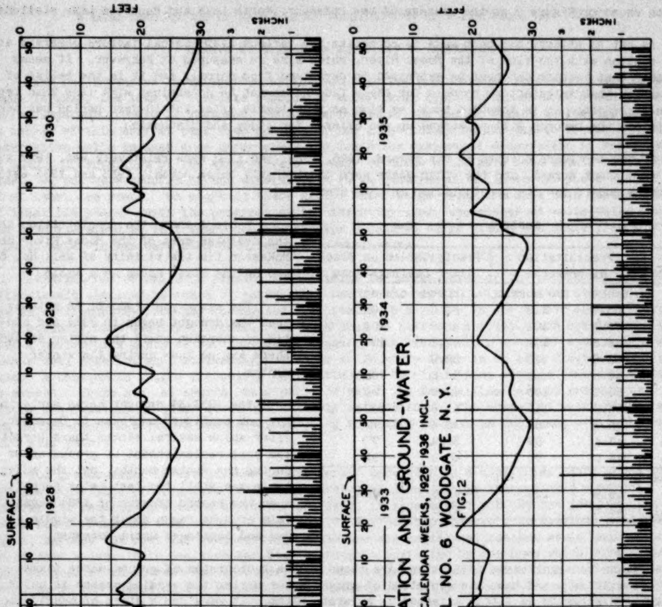
Measurements are made from a bench-mark at the surface of the ground, the elevation of which is about 1480. The well is in a level area of glacial sand at Woodgate (White Lake Corners), shown on the McKeever sheet, United States Geological Survey map. This area appears to be a delta-deposit formed in an ancient glacial lake. The ground-surface slopes gently in all directions from the well. The maximum fluctuation during the 10-year period is slightly in excess of 16 feet; that is, the water-table has varied from 13.8 feet to 30.1 feet below the ground surface. The fluctuation of the 10-year mean stage, shown by the heavy line, is about 8.6 feet. The water-table, therefore, is well below the root-zone at all times.

Observations are made weekly, with a steel tape. A recording gage has been operated during parts of two summers, but the results have not been entirely satisfactory.

Two other wells, distant about one-quarter mile on either side of Well No. 6, have been observed as a check, and have been found to follow the regimen of No. 6 very closely. Another well, similarly situated in a level area of glacial sand and distant about eight miles north-



westerly from No. 6, has been observed quite frequently since 1928 and has been in general agreement with the Woodgate well. Two years ago a well was located in an area having similar characteristics about 3-1/2 miles north of No. 6. The regimen of this well has followed No. 6 very closely.



PRECIPITATION AND GROUND-WATER

BY CALENDAR WEEKS, 1926-1936 INCL.

WELL NO. 6 WOODGATE N. Y.

FIG. 2

Since September 1934 a rain-gage has been maintained at Well No. 6, and during the whole period rain-gages have been maintained at McKeever, eight miles north of the well, and at North Lake, ten miles east. The McKeever station is equipped with an anemometer, maximum and minimum thermometers, a psychrometer, a Friez hygrothermograph, and a 4-foot evaporation-pan, in addition to the rain-gage. These instruments have been in operation nearly ten years. The precipitation shown on Figure 2 is the average of the McKeever, North Lake, and Raquette Lake stations.

As yet no attempt has been made to correlate the various hydrological factors observed at this station with the flow of the Moose River, which also is measured at McKeever. It seems probable that results can best be expressed in departure from normal, and it is the belief of the writer that satisfactory normals for these factors cannot be determined with less than ten years of record. It is intended that, as soon as practicable after the 10-year period has been completed, the records will be worked up and offered for study and discussion.

Of the ten years covered by the record, 1926, 1929, and 1932 were relatively wet, 1927 and 1928 were about normal, and the other years were considerably below normal, 1933 and 1934 establishing a record for low precipitation in this area.

Table 1

Year	Precipitation at McKeever		Precipitation on Black River Drainage-Area	
	inches	o/o normal	inches	o/o normal
1926	55.4	113	50.7	108
1927	49.1	101	48.9	104
1928	49.8	102	47.1	100
1929	53.6	110	52.9	112
1930	44.2	91	38.5	82
1931	50.1	103	42.8	91
1932	56.9	116	51.8	110
1933	42.1	86	36.4	77
1934	43.4	89	36.4	77
1935	44.0	90	42.8	91
10-year mean	48.9	100	44.8	95
Normal	48.8		47.0	

Table 1 shows the precipitation on the drainage-area of the Moose River above McKeever (in the vicinity of Well No. 6) and on the Black River as a whole.

The water-year 1930-31 is notable in that the drought began in July and continued unbroken until the spring of 1931. There was no thaw during the winter months.

The 1933-34 drought began early in May and continued unbroken to December, after which several winter thaws permitted some replenishment of ground-water during the winter months, but the water-table was still two feet below normal when the record drought of 1934 began. This drought began about the middle of May and continued until November.

A number of significant indications are shown on the hydrographs of ground-water stage. First, it will be noted that the depletion of ground-water during the growing season is quite regular, and seems to be little affected by moderate rains. It requires a storm of considerable magnitude to cause a replenishment of ground-water during the growing season. The explanation may be that only a heavy rain produces water enough to percolate below the zone of vegetation-roots before it is withdrawn through the vital processes of the growing plants. A rain of moderate proportions in November or December, after the dormant period has begun, causes a relatively great rise of ground-water.

Although the soil at this station is of glacial sand, so pervious that there is little surface-runoff even during the spring thaw, percolation appears to be very slow; several days must elapse before the water passes below the root-zone.

The hydrograph of stage during the long cold winter of 1930-31 continued nearly level during January and most of February, and fell only 0.5 foot from January 1 to March 1. The fact that stream-flow was maintained in fair volume during this period suggests that there may have been some melting of snow at the ground-surface by terrestrial heat.

At McKeever, the flow from the drainage-area tributary to the Moose River is recorded by the United States Geological Survey, and at the meteorological station of the Black River Regulating District, temperature, humidity, wind-movement and wind-velocity, evaporation, and precipitation have been measured for nearly 10 years. It is hoped that these records will be of some value in correlating the various factors which control the disposition of precipitation and perhaps in forecasting runoff.

Black River Regulating District,
Watertown, New York

A LONG-TERM RECORD OF WATER-LEVEL FLUCTUATIONS AT PLAINFIELD, NEW JERSEY

Howard T. Critchlow and Henry C. Barksdale

When the intensive investigation of the quantitative ground-water problems in New Jersey was begun in 1923, the lack of adequate records of water-level fluctuations in most areas immediately became apparent. David G. Thompson, Senior Geologist of the United States Geological Survey, was in charge of this work at that time and one of the first things he did was to locate a number of observation-wells in each area under study and begin the systematic measurement of water-levels in them. Observations of the water-levels in many of these wells have been maintained since that time. We now have records of the water-levels in 44 observation-wells in the State for periods of at least ten years. On eight of these wells, water-stage recorders have been maintained for at least ten years. With the progress of the investigations, the number of wells being observed has been increased so that there are now perhaps a hundred wells within the State from which records of water-levels have been obtained for several years.

It might not be amiss in passing to emphasize the great value of the continuous records of water-levels obtained by means of water-stage recorders, particularly in areas affected by pumpage which fluctuates from day to day and from season to season. In one of our observation-wells we frequently have a daily fluctuation of more than 15 feet and a fluctuation considerably larger over a period of a month or so. Obviously measurements taken once a month or even once a day in such a well might be very misleading. Even in wells where there is no wide fluctuation of water-level, a continuous record frequently calls attention to significant details that might otherwise be missed. There are, of course, many wells in which the fluctuations are so gradual that periodical observations of water-level are entirely satisfactory. The number of water-stage recorders on observation-wells in New Jersey is being increased as fast as the funds available for the work will permit.

The ground-water investigations in New Jersey have been on a continuing basis since 1923 and the importance of long-term records of water-levels has become increasingly apparent. When some of the records were three or four years long, it seemed that the returns for the time and money spent obtaining them were diminishing. It was decided, however, to continue measuring the wells, because the cost was comparatively small and the additional records would unquestionably be of some value. This decision has been thoroughly justified by the uses which have since been made of some of these records. However, even the longest of the records of ground-water levels obtained in the course of the present investigations are not yet comparable with the long-term records of precipitation and of pumpage from public supplies which are available in the State.

Unquestionably the longest series of measurements of ground-water levels in New Jersey is that made by the officials of the Plainfield-Union Water Company at their Netherwood Plant. This record is probably also one of the longest uninterrupted records of ground-water level in the United States. It was begun in 1891, about the time the Plant was built, and has been continued to the present time. Daily measurements of the water-level in a test-well at the Plant have been made during most of the period.

Rudolf Hering and, later, L. L. Tribus were the consulting engineers engaged on the construction and early operation of the Plant. One of these gentlemen is probably responsible for the beginning of the record, but most of the credit for continuing this long series of measurements is due to Amos Andrews, who was for many years superintendent. F. L. Winslow, secretary of the Company, furnished the authors with a record of the water-levels in this well and with a graph prepared by Mr. Andrews showing the fluctuations of the water-level and the related factors of precipitation and pumpage in essentially the same form in which it is presented herewith.

The well-field is situated in an area of stratified glacial drift which rests upon sandstone and shale of Triassic age at a depth of about 75 feet below the surface. The water-bearing sand is overlain by clay so that the intake-area is necessarily at some distance from the wells. When the Plant was first established, the entire supply was drawn from 20 wells, all of which were pumped by direct suction and drew their water from the drift. In 1910 a number of wells drawing from the underlying rock were drilled at the plant. These rock-wells extend to a depth of about 500 feet. At present the supply is pumped by air-lift from 16 rock-wells and from 24 wells tapping the drift. Since the installation of the rock-wells, a record of the water-levels in them has also been kept. In general, the water-level in the rock-wells has been about 15 feet below that in the wells to the drift.

The fluctuations of water-level in a well tapping the drift are shown in Figure 1, together with records of the total pumpage from the Netherwood Station and of the precipitation at the United States Weather Bureau Station at Plainfield from 1891 to 1935. The bars at the top of

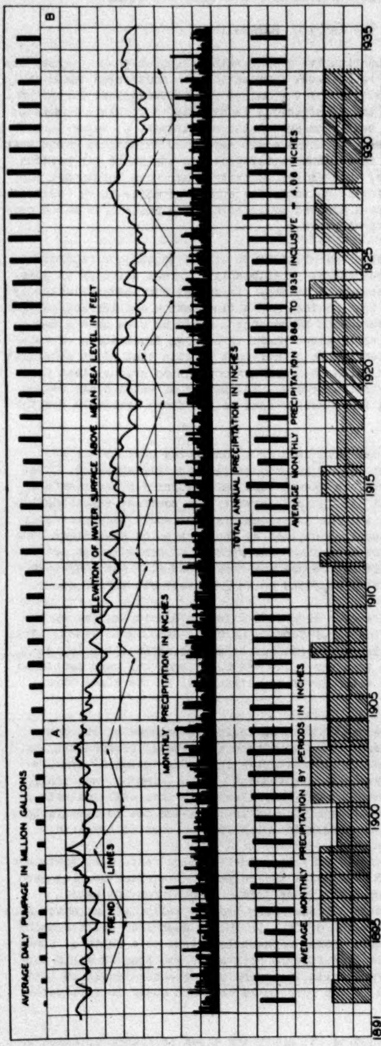


FIG. 1— DIAGRAM SHOWING FLUCTUATIONS OF WATER-LEVEL IN A GRAVEL WELL, NETHERWOOD STATION, PLAINFIELD-UNION WATER COMPANY, 1891-1935, AND RECORDS OF PUMPAGE AND PRECIPITATION DURING SAME PERIOD

the diagram represent the average daily rate of pumpage each year. It will be noted that there has been a gradual, but somewhat irregular increase in pumpage from one-half million gallons daily in 1892 to about seven million gallons daily in 1931. The decreased rate of pumpage since 1931 was probably due to the transfer of a part of the load to another station. The wavy line below the pumpage-diagram represents the elevation of the water-surface in the observation-well referred to mean sea-level. The elevation of the ground-surface at the station is about 120 feet above mean sea-level. Below the line representing the elevation of the water-surface are shown the monthly and annual precipitation in inches at Plainfield and the average monthly precipitation by periods.

There is a gradual decline of the water-level throughout the period of record corresponding to the increase in pumpage. There are also intermediate fluctuations which appear to be the result of wet or dry periods and still smaller fluctuations which are probably due to seasonal variations in pumpage or to short periods of excessive rainfall. The beginning and end of the periods at the bottom of the diagram were determined by drawing straight lines through the record of water-levels to represent the average trend during each intermediate fluctuation. The periods were assumed to end where the two trend-lines intersected. The arrows below the line representing water-levels on the diagram show the direction of the intermediate fluctuations in these periods. The average monthly precipitation for each period was then computed and plotted. The average monthly precipitation at Plainfield from 1888 to 1935 was 4.08 inches. Almost invariably the average precipitation was high during periods of rising trend and low during periods of declining trend. To a lesser extent, the same relation is brought out by comparing the annual precipitation with the water-level curve.

This record is presented for its general hydrologic interest since it is probably among the longest records of water-level in the country. No attempt will be made in this paper to analyze it with a view to determining the safe yield or other characteristics of the water-bearing beds tapped by the well. Perhaps its greatest value lies in the fact that it serves to emphasize the value of long-term records and the necessity for considering all the factors which may affect the water-levels in wells before drawing too definite conclusions. Periods of several years might be selected from this record and used alone to demonstrate either that the water-level was falling rapidly with a small increase in pumpage, or that it was rising because of heavy precipitation in spite of increased pumpage. The longer record shows that both pumpage and precipitation were having their normal effect, although the effect of one was sometimes masked by the effect of the other for several years at a time.

New Jersey State Water Policy Commission,
Trenton, New Jersey

DECLINE OF ARTESIAN HEAD IN WEST-CENTRAL SOUTH DAKOTA

Thomas W. Robinson

(Published with the approval of the Director, U. S. Geological Survey)

During the summer of 1935 the United States Geological Survey, in cooperation with the South Dakota Geological Survey, made a field-study and report of the artesian conditions in the west-central part of South Dakota. This study covered the semiarid plains-region between the Black Hills uplift and tne Missouri River, in which the Pierre shale is at or very near the surface. One of the important facts brought out by this study was the large decline in artesian head since development of the artesian basin began in the early 1890's.

The Dakota sandstone, which forms the principal source of artesian water-supply in west-central South Dakota, underlies all of the western part of the State, from its outcrop in the Black Hills uplift eastward to the Missouri River and beyond. It has a steep outward dip on the sides of the uplift, which in a short distance carries it far beneath the adjoining plains, where it is overlain by a thick body of Upper Cretaceous strata, at the top of which is the effectively impermeable Pierre shale. Except in a narrow strip adjoining the outcrop area, the Dakota sandstone lies at so great a depth for a distance of nearly 100 miles to the east that the only wells which have penetrated it are oil-prospects. Still farther east, however, beginning about midway between the Black Hills and the Missouri River, where the dip is not so great, or where the cover is not so thick, the Dakota sandstone lies within reach of the water-well driller and has been developed extensively for water-supply.

According to Darton [see 1 of "References" at end of paper], a part of the intake-area of the Dakota sandstone is in its elevated outcrop-zone in the Black Hills. This outcrop-zone occurs for the most part at altitudes of 3100 to 3500 feet. Here the sandstone receives water, part of which comes from rainfall and part from streams that flow across the outcrop. The water thus absorbed by the sandstone percolates down the dip, through the interstices of the rock, and passes far beneath the surface. In general, the direction of movement of the water is outward from the Black Hills and then eastward across the State, as shown by the map of the piezometric surface (Fig. 1). Russell [2] has raised a question whether the Dakota sandstone, instead of being a continuous bed or zone extending from its outcrop eastward across the State, may consist of discontinuous lenses separated by more or less impervious clay. However, other writers have not considered that the evidence definitely supports Russell's contention [3].

Since development of the artesian water-supply began in western South Dakota there has been a pronounced decline in the static water-level. The decline at first was probably local, but with extensive development it has become general and at the present time affects all of the west-central part of the State.

No detailed records of the rate of decline of the artesian head are available, but from a few records of head at different times some conclusions can be reached. The data on the artesian head during the early period of development are drawn from the early work of Nettleton [4], Darton [5], and Todd [6], and from the later work of Derr [7] and Berg [8].

The earliest record of artesian head was obtained from the first well drilled to supply the City of Chamberlain with water. This well, finished in May 1891, was started at an altitude of 1547 feet above sea-level and was drilled to a deptn of 785 feet, at which it yielded a flow of 529 gallons a minute. The hydrostatic pressure at the end of a 24-hour test was 122 pounds to the square inch, which is equivalent to a head of about 280 feet. In April 1900, the flow had decreased to not more than 40 gallons a minute. Part of this decrease in flow was due, no doubt, to interference from six power-wells drilled in the city at a lower altitude. A second well, drilled in August 1900, was started at a point ten feet higher, was carried to a depth of 966 feet, and had a hydrostatic pressure of 55 pounds to the square inch, equivalent to a head of about 125 feet.

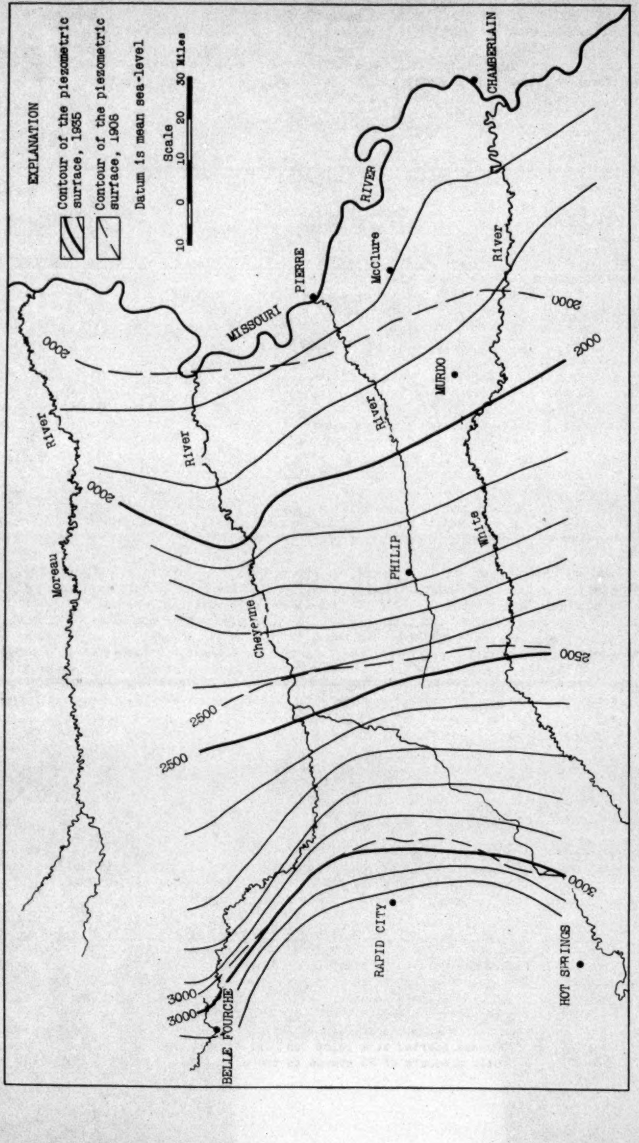

EXPLANATION
Contour of the piezometric surface, 1935
Contour of the piezometric surface, 1906
Datum is mean sea-level
Scale
10 0 10 20 30 Miles
CHAMBERLAIN
MISSOURI
RIVER
PIERRE
McClure
River
MURDO
PHILIP
White
River
Moreau
River
Cheyenne
River
RAPID CITY
HOT SPRINGS
BELLE FOURCHE
2000
2000
2000
2000
2500
2500
2500
3000
3000
3000

FIG. 1—MAP OF A PART OF WESTERN SOUTH DAKOTA SHOWING THE HEAD OF THE ARTESIAN WATER IN THE DAKOTA SANDSTONE

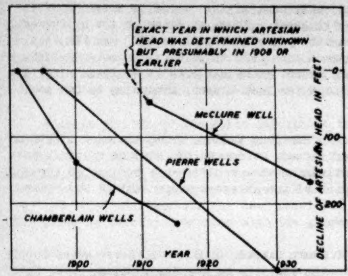


FIG. 2—AMOUNT OF DECLINE OF ARTESIAN HEAD IN WEST-CENTRAL SOUTH DAKOTA

From these data it is calculated that the altitude of the piezometric surface at Chamberlain was 1828 feet in May 1891, as recorded in the first well, and 1684 feet in August 1900, as recorded in the second well. Thus in the period from May 1891 to August 1900, there was a drop in head of about 140 feet, or an average of about 15 feet a year. No other comparable measurements of water-level on these wells are available. However, some idea of the amount of decline in head in this locality between 1900 and 1915 is afforded by comparison with a measurement of head on the city well of Oacoma, three miles west of Chamberlain. This well was drilled in 1912 on land 1388 feet above sea-level. The pressure recorded by Derr [9] on October 13, 1915, was 95 pounds to the square inch, giving a head of 1607 feet with reference to sea level. By a direct comparison of the two wells the decline over the 15-year period would appear to be 77 feet; however, as the well at Oacoma is up the hydraulic gradient, the piezometric surface there is higher than at Chamberlain, and the amount of decline is greater by an amount equal to the difference in head between the two wells. This difference, as estimated from the map of the piezometric surface (Fig. 1), prepared in 1935, is between 10 and 20 feet. Accordingly, the amount of decline between 1900 and 1915 was about 90 feet, an average of six feet a year. The total decline between 1891, when the first well was drilled at Chamberlain, and in 1915 was about 230 feet, and by 1935 it was undoubtedly greater. The total amount of decline and the average rate are shown on the hydrogram reproduced in Figure 2.

At Pierre one of the first wells was drilled for the Pierre Natural Gas and Power Company. This well was drilled either in 1895 or 1896 and, according to Todd [10], had a pressure of 210 pounds to the square inch. From Todd's description the altitude at the well is estimated at about 1440 feet, and the head when drilled at about 1920 feet, with reference to sea-level. In 1930 a well was drilled by the City of Pierre at an altitude of 1440 feet. The original shut-in pressure of this well was reported by the driller as 80 pounds to the square inch, equivalent to a pressure of 184 feet, making the altitude of the static water-level about 1620 feet. Thus in the 35-year period from 1895 to 1930 the decline in head at Pierre amounted to about 300 feet, an average of 8.5 feet a year. This decline is one of the greatest known in the United States.

The McClure Well (sec. 31 or 32, T. 108 N, R. 78 E) in northwestern Lyman County, about 20 miles southeast of Pierre, also affords data on the decline in head. According to Darton [11], the altitude of the well was 1917 feet and the pressure 20 pounds to the square inch, or sufficient to raise the water 1963 feet above sea-level. The year in which this pressure was determined is not known, but it was presumably 1908 or earlier. A later report by Derr [12] indicates that the well ceased to flow about 1911. Between the year in which Darton's reported pressure was measured and the year in which the well ceased to flow the decline in head amounted to 46 feet. It was not possible to obtain a measurement of artesian head in this well during the investigation of 1935, but by interpolation from the contours of the map of the piezometric surface (Fig. 1) it was estimated that in 1935 the head at the locality of the well would stand between 1790 and 1800 feet with reference to sea-level. Thus in the 24-year period since the well ceased to flow, the decline in head has amounted to about 120 feet, an average of five feet a year. The total decline in head since the measurement reported by Darton is about 165 feet.

Some idea of the regional decline in head over the area is afforded by a comparison of Darton's map of the piezometric surface [13] published in 1908 with the map prepared in 1935 (Fig. 1). A comparison of the contour-lines shows a decline in head in the eastern and east-central parts of western South Dakota ranging from 50 to 250 feet.

In the extreme western part of South Dakota, one to thirteen miles from the outcrop-zone of the Dakota sandstone, recent measurements compared with data reported by Darton [14] indicate that the decline has not been so great as farther east. This difference may be due in part to the fact that records for the western part do not extend back to such early years as those for the eastern part. The longest available record for a well near the outcrop-area, that of the well at Vale, about 13 miles away, shows a decline of only 20.5 feet in a period that may have been as long as 26 years or as short as 18 years. Interpolation from the contours on Darton's map indicates that the decline at some wells may have been as much as 80 feet.

The most rapid decline in head occurred in the early part of the period of artesian development, when the artesian pressure and flow were still great. Thus, as shown on the hydrogram (Fig. 2),the recorded decline at Chamberlain in the nine years from 1891 to 1900 was 140 feet, an average of about 15 feet a year, but in the 15 years from 1900 to 1915 it was only 90 feet, an average of about six feet a year. The decline in recent years has been at a slower rate, the average apparently ranging from less than one foot to a few feet a year, according to the local draft.

The greatest decline recorded has occurred in the Missouri Valley, along the east margin of the area studied. This difference is partly due, as already noted, to the absence of early records for other parts of the area, but there is doubtless an actual difference because of the much greater draft in the Missouri Valley and the part of the artesian basin east of the river.

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U. S. Geological Survey,
Washington, D. C.

THE RELATION OF THE DROUGHT OF 1934 TO GROUND-WATER SUPPLIES IN THE JAMES AND SHEYENNE RIVER-BASINS OF NORTH AND SOUTH DAKOTA

A. N. Sayre

(Published with the approval of the Director, U. S. Geological Survey)

The water-shortage caused by the drought of 1934 in the Middle West drew nation-wide attention to the lack of adequate information on the relation of precipitation to water-supplies. The shortage was especially severe in the Dakotas because precipitation had been below normal in North Dakota since 1930 and in South Dakota since 1931. Many wells and springs failed, numerous streams ceased to flow, and levels of water in lakes and ponds declined until some of them became completely dry. Many of the inhabitants felt great concern lest the water-supplies of the area had been permanently depleted.

In the spring of 1935 the Army engineers began an investigation to determine the extent of the water-shortage in the valleys of the James and the Sheyenne rivers, which occupy most of the eastern part of the two Dakotas, and to study the possibility of regulating the flow of these streams. In connection with this investigation, the writer was assigned by the United States Geological Survey to study ground-water conditions in the area. During the course of the investigation 16 cities and towns were visited, and information regarding their water-supplies was obtained, especially with reference to the depletion of their ground-water supplies.

The area is underlain by glacial deposits, which are in turn underlain by rocks of Cretaceous age, in the following order from the top down: Pierre shale, Niobrara formation, Benton group, and Dakota sandstone. The bodies of sand and gravel in the glacial drift constitute ground-water reservoirs that yield potable water to many wells in the area. The deposits of glacial Lake Agassiz in the Red River Valley reach a thickness of nearly 300 feet in the center of the Valley and contain thick beds of sand and gravel that yield potable water to wells.

A large portion of the wells throughout the area draw from the Dakota sandstone. The Benton group and the Niobrara formation yield water to many wells in South Dakota, and the Pierre shale yields highly mineralized water to a few wells scattered through the area. The water from the Dakota, Benton, and Niobrara formations also has a high mineral-content. The decline in head in the wells in the Dakota sandstone, which has been in progress for about 50 years, is evidence that the artesian reservoir has been developed nearly or quite to the limit of its capacity. This paper is chiefly concerned with the ground-water supplies of the glacial drift.

The water in all the ground-water reservoirs is derived chiefly from the precipitation that falls upon the outcrop-areas of the water-bearing beds, although in some places streams that cross the outcrop may contribute a certain amount of recharge. Other things being equal, the amount of recharge or intake varies with the extent and permeability of the outcrop-area and with the amount of precipitation.

The water moves through the aquifer at a rate varying with the permeability of the water-bearing beds and the hydraulic gradient. The effects of deficiency in precipitation on the outcrop-area of a very large aquifer may be reflected rather quickly in the adjacent area by decline in the water-levels in wells, but as the underground movement is slow, even under the most favorable conditions, the deficiency is not likely to be noticeable at any great distance from the outcrop-area. On the other hand, the effect of deficiency in precipitation on the outcrop-area of a small aquifer is likely to be reflected rather quickly by lower ground-water levels throughout the water-bearing bed, and continued deficiency is likely to be followed by complete drainage of the aquifer through springs and wells. Thus the effect of deficiency in precipitation on the water-supply of any water-bearing bed is dependent largely upon its thickness and extent and to some degree upon its relation to the topography.

Three of the municipalities visited depend wholly on surface water-supplies; these are Fargo, North Dakota, and Mitchell and Aberdeen, South Dakota.

The supply for Huron, South Dakota has been drawn from a reservoir on the James River for many years, but in 1934 the failure of this source caused the city officials to explore the adjacent area for ground-water. On an 80-acre tract four miles west of the city, four wells, equally spaced, were drilled into the glacial drift to a depth of about 85 feet. These wells drew water from about 30 feet of sand. They were pumped at the rate of about 400,000 to 600,000 gallons a day from November 1934 to April 12, 1935, and during that time the water-level had declined from 7.25 to 22.5 feet below the surface. The wells were not pumped from April 12 to May 1, and the water-level rose to 12 feet below the surface, or within 4.75 feet of the original level. The wells were again pumped from May 1 to July 1 at a rate ranging from 600,000 to 1,200,000 gallons a day, and the water-level declined to about 29 feet. After July 1 the wells were shut down, and the water-supply was again taken from the river. The pumping was not continued long enough to determine whether this ground-water reservoir would continuously supply sufficient water for the city of Huron. However, the rapid rise in the water-level from April 12 to May 1 indicated large permeability and showed that the underground reservoir had not been seriously depleted by the drought or by pumping.

Redfield, South Dakota, and Lisbon, North Dakota, are supplied with water from wells in the Dakota sandstone, and this supply, although the water contains objectionable amounts of mineral matter, has been adequate up to the present time.

Oakes and Cooperstown, North Dakota, draw their water-supplies from large ground-water reservoirs, and no appreciable lowering of the water-level in wells was reported in these towns.

New Rockford and Jamestown, North Dakota, are on the James River. Both towns draw their water-supplies from well-fields, in which the wells are 70 feet or less apart. Large bodies of sand and gravel in the glacial drift constitute the ground-water reservoirs. New Rockford reported a decline of water-level in the city wells of seven feet in fourteen years, and Jamestown reported three feet in four years. In nearby wells in both areas the decline in water-level was negligible, showing that the decline in the city wells is due to heavy pumping from small areas rather than to depletion of the supply.

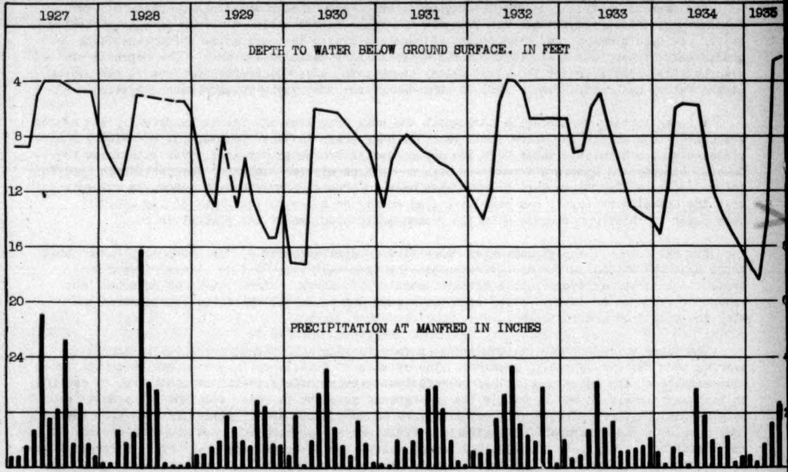

FIG. 1—DIAGRAM SHOWING FLUCTUATION IN WATER-LEVEL IN CITY WELL AT HARVEY, NORTH DAKOTA, AND PRECIPITATION AT MANFRED, NORTH DAKOTA

Moorhead, Minnesota, on the Red River opposite Fargo, draws its supply from two well-fields a little over a mile apart in the deposits of glacial Lake Agassiz. Each well-field consists of three wells within a radius of 100 feet, and the wells range in depth from 195 to 273 feet. In the older field the water-level has been lowered from six feet below the surface in 1914 to 133 feet below the surface in the spring of 1935; in the newer field it has been lowered from 80 feet in 1927 to 115 feet in 1935. Meager data in regard to other wells in the city indicate that the great lowering of the water-level in the wells owned by the city is local and is largely due to excessive pumping from small areas.

At Harvey, North Dakota, the city water-supply is drawn from two wells 41 feet deep in the Sheyenne River Valley 2-1/2 miles northeast of the city. The gravel from which these wells draw their water is overlain by eight feet of silt and extends to a depth of at least 82 feet, which is the depth of the test-wells drilled into it. The outcrop-area of this gravel is not definitely known but is believed to be on the terraces of the Valley and in the Valley itself south of the pumping plant. The average pumpage in summer is about 200,000 gallons a day and in winter about 100,000 gallons a day. Water-level measurements have been made monthly in one of the city wells since February 1, 1927. The measurements are made in the morning, after the pumps have been idle for several hours. The accompanying graph (Fig. 1) shows the fluctuations of the water-level in this well and the monthly precipitation during the same period at Manfred, North Dakota, eight miles southeast of Harvey.

The record shows that the water-level usually reaches a high stage in May or June, after which it declines, slowly during July and August and rather rapidly during the succeeding months. This decline during the summer and winter is usually followed by a rapid rise in March and April. In June 1927 the water-level was four feet below the surface, and it has generally risen to nearly the same high level each spring. In winter, however, it has tended to decline to successively lower levels, going as low as 18 feet 2 inches below the surface in March 1935. Since March 1935 heavy precipitation has occurred, and the water-level in this well has risen above the highest level previously recorded--reaching 3 feet 6 inches below the surface May 1 and 3 feet 4 inches June 1, 1935.

Little or no recharge occurs during the winter because of the low precipitation and because the ground is frozen and, therefore, is more or less impermeable to water. The winter precipitation is stored at or near the surface and seeps downward to the zone of saturation only after the ground thaws. This recharge, with the addition of the recharge that occurs from precipitation during the interval between the thawing of the ground and the beginning of the growing season, causes the rapid rise in the water-level during the spring. The fact that the recharge is so quickly reflected in the city well probably indicates that the recharge-area is nearby. During the summer only moderate amounts of recharge occur because most of the precipitation is lost through runoff, evaporation, and the transpiration of plants; thus the recharge in summer is somewhat less than the pumpage and natural draft, and therefore the water-level declines. During the winter the water-level continues to decline because the recharge is low and not sufficient to make up for that lost by pumpage and by percolation away from the area through the aquifer.

The total recharge to the zone of saturation in this aquifer appears to be great, not only in years with normal precipitation but also in years when the precipitation is considerably below normal, and as the water-level each year reaches about the same high stage, it seems evident that the safe yield of the ground-water reservoir is not being exceeded and that the water-supply has not been seriously depleted by the drought.

Several of the towns draw their water-supplies from aquifers so small that deficiencies in precipitation are quickly reflected in lowered water-levels and even by the complete failure of wells. In general, such aquifers are shallow and have a small area of recharge.

At Lamoure, North Dakota, the aquifer extends from about nine to 14 feet below the surface. When the 15-foot well used for municipal supply was dug, in 1918, the water-level was six feet below the surface, according to Oliver Johnson, who has charge of the well. In March 1934 the water-level had dropped to about nine feet below the surface, and during the summer of 1934 the water-level when the pump was in operation was only a few inches above the pump-intake near the bottom of the well. Although the supply did not fail, there was cause for considerable anxiety. In March 1935 the static water-level was 11.4 feet below the surface.

At Sheyenne, North Dakota, the aquifer extends from the surface to a depth of 25 feet. There is no municipal supply, and families are served by private wells, many of which failed during 1934.

At Grace City, North Dakota, the aquifer extends from about 17 to 20 feet below the surface. Private wells supply the town and during 1934 only four out of about 40 wells in the town contained water. These four wells were about 22 feet deep, or about four feet deeper than the wells that failed.

At Valley City, North Dakota, on the Sheyenne River, the water-supply has been taken from wells in a comparatively small body of gravel within and north of the city. Water-levels have been declining over a period of many years and in 1933 the water-level in the most recent of the wells became alarmingly low. In 1933 water from the Sheyenne River was diverted into an abandoned gravel-pit in the northern part of town, where it percolated into the gravel, thus raising the local ground-water level. This artificial recharge has apparently solved the water-supply problem for the city and, in order to insure a constant supply of water from the river during time of drought, a reservoir has been formed by the construction of a dam on the Sheyenne about 10 miles above Valley City.

Conclusions

Many of the small water-bearing beds in the glacial drift of the James and Sheyenne River basins were seriously depleted during the drought of 1934, and as a result numerous shallow wells failed; the flow of many springs was also greatly reduced or ceased entirely, causing great reduction in the flow of the streams of the area. On the other hand, the larger and deeper reservoirs were not seriously depleted, although there was a general decline of the water-table in the outcrop-areas.

The water-levels rose quickly in the intake-areas after recharge, as indicated by the well at Harvey.

At greater distances from the outcrop-areas no great depletion due to the drought occurred, as is shown by the wells at Oakes and Cooperstown. The decline reported in such cities as Jamestown and New Rockford, North Dakota, and Moorhead, Minnesota, was due chiefly to excessive pumping from small areas rather than to depletion of the supply because of lack of recharge; this is illustrated by the rapid recovery of the water-level at Huron, South Dakota, when pumping in the well-field ceased.

The failure of farm wells was not so serious as it seemed at first. Many farm wells are sunk only a short distance into the first water-bearing formation encountered, and therefore a small decline may cause the water-level to fall below the bottom of such a well, with the result that the well fails. Many of these wells would not have failed if they had extended through the water-bearing formation or, where the sand is thin, far enough into the glacial drift to tap lower beds of sand and gravel. Many of the wells that failed could have been restored by deepening them. Considerable additional water-supplies could be developed in the glacial drift of the area by careful exploration and proper well-spacing and well-construction.

U. S. Geological Survey,
Washington, D. C.

THE RECOVERY OF GROUND-WATER LEVELS IN NEBRASKA IN 1935

Leland K. Wenzel

(Published with the approval of the Director, U. S. Geological Survey)

A program of water-level measurements in about 350 wells scattered throughout Nebraska was begun in 1934 by the United States Geological Survey in cooperation with the Conservation and Survey Division of the University of Nebraska (see L. K. Wenzel, A state-wide program of periodic measurements of ground-water level in Nebraska, Trans. Amer. Geophys. Union, 16th annual meeting, pp. 495-498, 1935). Included in this program were about 60 wells in the Platte River Valley on which periodic measurements were started in 1930. Observations on the 350 wells were continued in 1935 at about monthly intervals and the measurements collected are now being prepared for publication as a paper of the Nebraska Geological Survey.

There was a general recovery of ground-water level in Nebraska in 1935 from the low drought-level of 1934 although the precipitation in the State in 1935 averaged only 97 per cent of normal. The average water-level in 252 control-wells rose without interruption from October, 1934, to July, 1935, the total rise amounting to 1.5 feet. This 9-month rise was followed by a 3-month decline to October and then by another rise to January, 1936. The average net rise of water-level in the 252 wells for the year ending October 1, 1935--that is, from the low level of 1934--was 0.63 foot and for the year ending January 1, 1936, it was 0.36 foot.

The water-levels in 184 out of a total of 275 wells on which satisfactory records were obtained, stood higher on January 1, 1936, than on January 1, 1935, and the water-levels in the remaining 91 wells stood lower. Thus, rises of water-level occurred in 67 per cent of the wells. There were net annual rises of less than 0.3 foot in 62 wells and net declines of less than 0.3 foot in 58 wells. Most of these relatively small changes in water-level are thought not to be significant. There were net annual changes in water-level of more than 0.3 foot in 155 wells. The water-levels rose in 122 of these wells and declined in 33. Thus significant rises of water-level occurred in about 44 per cent of the 275 wells and significant declines occurred in only about 12 per cent. There were net rises of water-level in 1935 of more than one foot in 49 wells in contrast to net declines of more than one foot in ten wells; and there were rises of more than two feet in ten wells in contrast to a decline of more than two feet in only one well. The maximum net rise was 5.63 feet in a well in western Nebraska and the maximum net decline was 4.43 feet in a well in the eastern part of the State.

Table 1--Average fluctuation in 1935 of water-level in groups of wells segregated according to different depths to the water-level

Depth of water-level below land-surface	Number of wells	Average fluctuation in 1935	Average change in 1935
ft		ft	ft
1 - 10	73	1.44	+0.33
10 - 20	68	1.67	+0.59
20 - 30	36	1.14	+0.59
30 - 40	19	1.02	+0.23
40 - 50	6	0.74	+0.27
50 - 60	6	0.28	-0.09
60 - 70	9	0.31	-0.11
70 - 80	7	0.36	-0.05
80 - 100	4	0.19	-0.16
100 - 150	8	0.17	+0.03
150 - 200	15	0.19	+0.11

The water-level fluctuations varied considerably in different wells. In general, the largest fluctuations were observed in shallow wells and the smallest fluctuations in the deepest wells, irrespective of the locations of the wells throughout the State. Table 1 gives the average fluctuation of water-level in 1935 in several groups of wells that have been segregated according to different depths to the water-level. The average net changes in water-level in the different groups of wells in 1935 are given also. All of the wells are believed to be in areas where water-table conditions exist, that is, where the water is not confined under artesian pressure.

There was an average rise of water-level in 41 wells in the central Platte River Valley in 1935 of about one foot, which brought the water-level back to about the stage it possessed January 1, 1934. The year 1935 was only the second year since 1930, when observations were begun, in which there occurred a net rise of consequence. In the other year, 1932, there was an average net rise of 0.24 foot. Despite the fact that the precipitation in the Valley has been considerably below normal since 1930, the average stage of the water-level at the end of 1935 was only 1.28 feet below the average level January 1, 1931, and only 0.13 foot below the level January 1, 1932.

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AN INTERPRETATION OF WATER-TABLE FLUCTUATIONS AT FOUR WELLS IN SOUTHERN CALIFORNIA

F. C. Ebert

(Published with the approval of the Director, U. S. Geological Survey)

The urban and agricultural development in most areas of southern California have depended on the underground water-resources of which more and more use has been made. It has been estimated that in the South Coastal Basin during the summer 90 per cent of the water-supply for irrigation and other purposes developed locally is obtained from underground sources [see 1 of "References" at end of paper]. Because of the economic importance of this resource, measurements of the depth of water-level are made regularly at hundreds of wells in the area to obtain knowledge of the draw-down and replenishment.

The South Coastal Basin of California is generally understood to include the coastal plain areas of Los Angeles and Orange counties, together with the inland drainage-areas of the Los Angeles, San Gabriel, and Santa Ana rivers, exclusive of the drainage-basin of the San Jacinto River, which is a tributary of the Santa Ana River. The entire South Coastal Basin has an area of about 2,500,000 acres, of which 45 per cent, principally valley-land, overlies productive ground-water basins. About 70 per cent of this valley-land is irrigated for domestic and industrial purposes. The rapidly increasing population of the area has now reached about 2,800,000 [2].

The climate is semiarid, with a wet season and a dry season, coinciding with winter and summer. The rainy season begins around the last of September and ends the early part of May. Between 90 and 95 per cent of the total rainfall occurs in this period. The precipitation varies greatly from year to year, the minimum since 1877 for Los Angeles, as reported by the United States Weather Bureau, being 5.59 inches in 1898-99 and the maximum being 38.18 inches in 1883-84. The rainfall also varies greatly in different parts of the area, being greatest in the mountainous regions and least on the valley-floors.

The South Coastal Basin is composed of structural valleys, low-lying hills, and mountain ranges. Crustal movements and fractures have caused some portions to be thrust upward, while other parts have been depressed, forming closed structural basins. These basins have been filled with alluvium, and extensive flood-plains have been built up by water-transportation of the weathered and eroded material from the steep mountain-slopes [3].

The materials composing the basin and flood-plain fills are largely from granitic and metamorphic rocks and have been distributed fairly evenly over the basins, the coarser materials being deposited near the apexes of the debris cones-where streams leave the mountain-canyons and the finer materials being laid down progressively as the stream slopes flatten.

Most of the streams are perennial in the mountain-stretches but intermittent in the valleys because the entire summer flow is either diverted at the mouths of the canyons for irrigation and domestic use or percolates into the basin-gravel soon after leaving the canyons.

The basin-gravel is replenished by percolation from surface-streams passing over it, by penetration of rainfall on the valley-floors, by underflow from adjacent basins, or by return-water from imported irrigation-supply. The depletion of underground supply is due to draft by pumped or flowing wells for domestic, irrigation, or industrial uses, by springs or rising waters at the outlets of the basins, or by evaporation and transpiration on moist areas.

The continuously increasing development in the area has resulted in a greater and greater draft on the ground-waters. In some basins replenishment from local sources has been inadequate, making it necessary to import water from other basins. The quantity of this imported water will be greatly increased in the immediate future by diversion from the Colorado River and Mono Basin. In some basins severe curtailment of ground-water use will become necessary, because the type of crops that can be grown cannot bear the cost of the relatively expensive imported water. In still other basins, although the water-table is at present below its former high levels, no special concern is felt as to possibility of overdraft, because it is generally considered that with

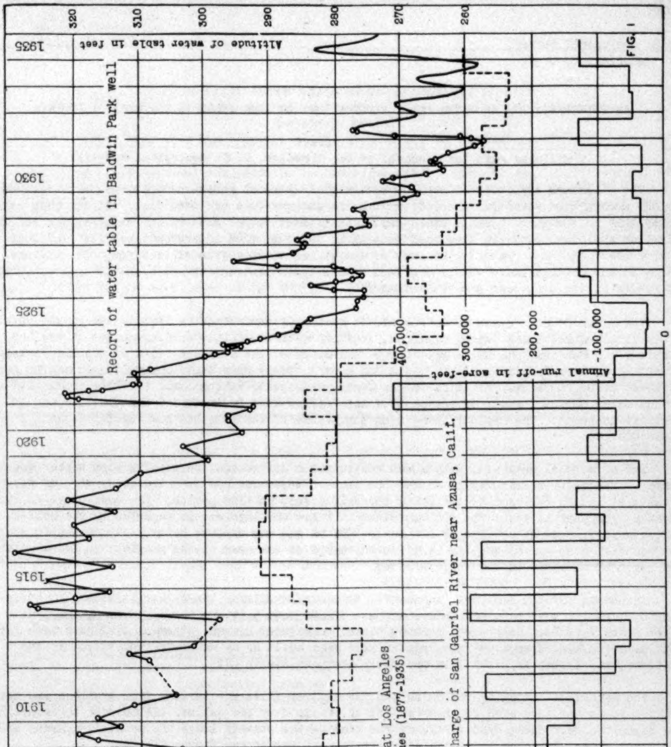


FIG. 1

our cyclic rainfall, replenishment will be adequate during favorable years.

Conservation-measures are being practiced more and more. These consist of spreading surplus surface-flows on the coarse gravel of the debris-cones at mouths of canyons, impounding such waters in shallow surface-reservoirs, and harrowing stream-channels to increase percolation and thus save water that might otherwise waste into the ocean. Where flood-control reservoirs have been built, stored water can ordinarily be released at such a rate that all of it can be absorbed into the gravel. Noted progress has been made in irrigation-practice, and considerable economy has resulted in a decreased use in water for that purpose.

Baldwin Park Well

The fluctuations in the Baldwin Park observation-well (No. 42, Water-Supply Paper 468) for the period 1905-36 are shown on Figure 1, together with the rainfall at Los Angeles and the discharge of the San Gabriel River near Azusa. The well is on the alluvial cone of the San Gabriel River, near the center of the basin, two miles east of the present stream-channel and about six miles from the mouth of the canyon.

This well, drilled solely for the purpose of observing the fluctuations in the ground-water table, is considered an accurate indicator of the ground-water conditions of the entire San Gabriel Basin. By State decision, the diversion of the flood-waters from the San Gabriel River depends on the altitude of the ground-water at this observation-well.

The San Gabriel Basin, which occupies the central and western part of the San Gabriel Valley, is a roughly semicircular depression surrounded by impervious formations. The materials that fill this basin are alluvial deposits laid down by the San Gabriel River. The only outlet is Whittier Narrows, at the southwest end of the Basin. A portion of the underground water passes out of the Basin as underground flow through the Narrows, but owing to the constriction of this area some water is forced to the surface and leaves the Basin as surface-flow. The amount of this rising water depends on the height of the water-table within the Basin. The specific yield of the Basin ranges from 11 to 20 per cent, and the computed storage-capacity for the zone 50 feet above and 50 feet below the water-table of January 1933 is 841,000 acre-feet [4].

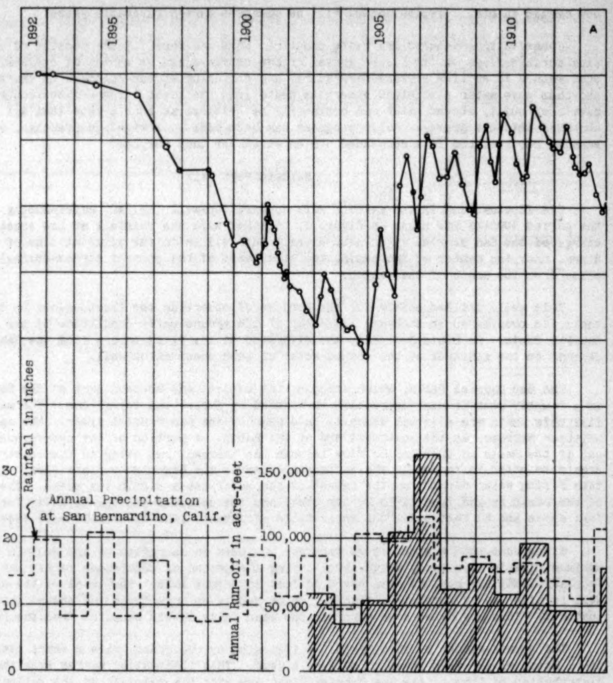
Since June 1932 a water-stage recorder has been in operation at the Baldwin Park Well. The maximum rise in mean daily water-level during the period of continuous record was 0.28 foot in February 1935; the maximum drop was 0.16 foot in August 1935. The level of the water in the Well is affected by barometric changes, which modify or accentuate the actual ground-water fluctuations. This may cause some error in the mean daily levels computed from the recorder-graph.

The ground-waters of this Basin, as indicated by the graph, have a sharp seasonal fluctuation, which ranges from three to 30 feet a year. This fluctuation varies with the quantity and distribution of flow of the San Gabriel River and with the rainfall on the valley-floor. The yearly draw-down is also variable, depending on the amount of rising water flowing out at the Narrows and the demand for domestic, irrigation, and industrial water. The record started in 1905, at the end of a period of very dry years. At that time the depth to water was 106 feet. During the following period of more than normal rainfall from 1905 to 1917 the Well showed a net rise of 36 feet and, for the ensuing period of deficient rainfall to January 1936, a net drop of 45 feet.

The rise of 26 feet in 1935 compares very favorably with the rise of 29 feet in 1922, even though the discharge of the San Gabriel River in 1935 was less than one-third of the discharge in 1922--125,000 and 401,000 acre-feet, respectively. The rainfall was more generally distributed throughout the winter in 1935 than in 1922 and was more general on the valley-floors. For example, the rainfall at Mount Wilson was 60.51 inches in 1922 and only 46.17 inches in 1935, but at Los Angeles the rainfall was 19.66 inches and 21.66 inches, respectively. In 1922 at Mount Wilson 48 per cent of the yearly total occurred in one month, and only four months had over three inches, whereas in 1935 only 25 per cent of the yearly total occurred in the maximum month and seven months had over three inches. In addition to this favorable distribution of rainfall, wastage out of the Basin by excessive flood-flow has been largely prevented by storage above Morris Dam, completed by the City of Pasadena in 1934. Some of this stored water was diverted to Pasadena for domestic use, but the rest was released at such a rate that channel-absorption and water-spreading conservation-activities prevented all but a little wastage into the ocean.

Williams Well

The Williams Well, for which a graph of ground-water levels is shown on Figure 2, is about three miles above the Bunker Hill Dike, adjacent to the present stream-channel of the Santa Ana



River, which ordinarily is a dry wash at this locality for many months of the year. The record from this Well has been used for many years as an indicator of the ground-water conditions in the upper Santa Ana or Bunker Hill Basin, which occupies the valley-area commonly known as San Bernardino Valley, exclusive of the Lytle and Devil Canyon Creek areas [5].

The ground-waters of this area are used for domestic, irrigation, and industrial supplies within the area and, in addition, waters rising to the surface at Bunker Hill Dike along the southwestern edge of the Basin, together with water from flowing and pumped wells, are exported out of the Basin. Replenishment is derived from streams debouching onto the area from the San Bernardino Mountains, of which the Santa Ana River is the largest, from rainfall-penetration on the valley-floor, and from percolation from adjacent basins. Water-conservation by spreading of surplus gravity-water on the debris-cone at the mouth of the Santa Ana Canyon to increase percolation is believed to be one of the first projects of this kind in California. This practice is now general on nearly all streams entering the area.

The Basin has been filled to considerable depth with alluvium, which is similar to that of the San Gabriel Basin in its water-yielding properties. The specific yield [6] ranges between four and 16 per cent, and the computed storage-capacity for the Basin in the 50 feet above and below the water-table of January 1933 is about 500,000 acre-feet.

The water in the Williams Well stood at the ground-surface in 1892 and 1893, when the record was first started. The series of relatively dry years that followed, together with an increase in the draft on the Basin for irrigation, caused the water to drop 42.5 feet by 1904. With the return of a series of wet years and the practicing of conservation-activities, the gravel of the

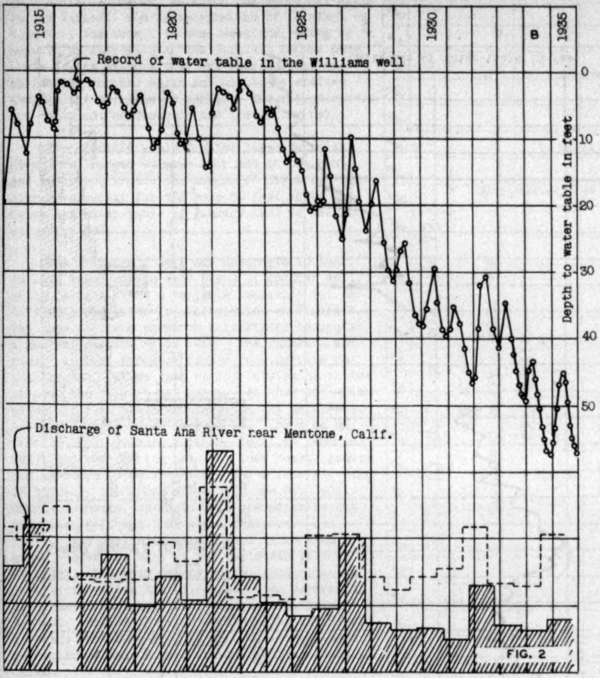


FIG. 2

Basin was replenished and the water-level rose 33.5 feet by 1907. Then the water-level dropped a little from 1911 to 1913 but soon recovered, and from 1916 to 1923 it remained within 10 feet of the surface except in 1921, when it dropped to a depth of 14 feet. Since 1923, with subnormal rainfall predominating and a very marked decrease in the runoff of the Santa Ana River necessitating a large increase in the pumping draft, the trend has been downward. At the end of 1935 the water-level in this Well was 57.5 feet below the ground-surface.

The well-graph shows a yearly cycle of recharge and draft. The recharge ranges between one foot and 20 feet and the draft between two and 15 feet. As this Well is not equipped with a recorder, the yearly cycle is indicated by frequent tape-measurements. The true magnitude of the yearly cycle may differ slightly from that shown on the graph.

J. B. Neff Well

The J. B. Neff Well (No. 41, Water-Supply Paper 468), shown on Figure 3, is in Orange County in the eastern section of the Coastal Plain, known as the Santa Ana River Area [7]. This Well is between the towns of Anaheim and Santa Ana, several miles west of the Santa Ana River. The record from this Well and its companion wells have been used freely as representing the history of the ground-water supply in the lowest part of the Santa Ana River Drainage-Basin.

The Coastal Plain represents a former wide bay which was gradually filled by alluvial debris that has been redistributed, in part at least, by oceanic waters as beach sand and gravel. The formation has been built up with a succession of sand-, gravel-, and clay-beds, whose constituent materials were transported to their present position by the Santa Ana, San Gabriel, and Los Angeles rivers [8]. The replenishment of the gravel of this area is effected by percolation

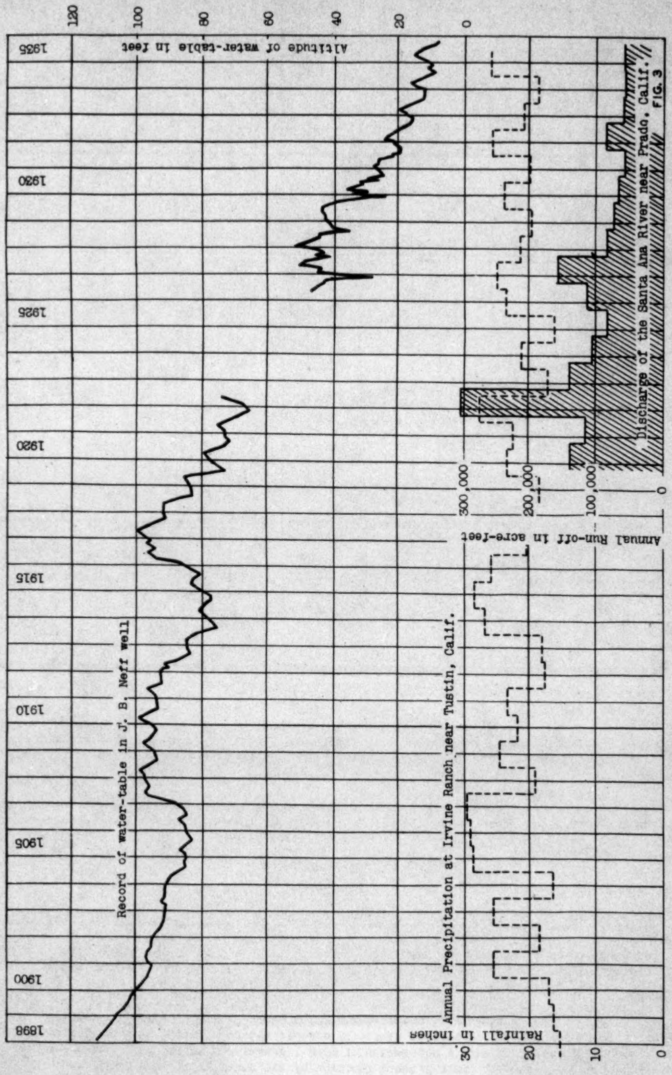

Altitude of water-table in feet
120
100
80
60
40
20
0
1935
1930
1925
1920
1915
1910
1905
1900
1898
Record of water-table in J. B. Neff well
Annual Precipitation at Irvine Ranch near Tustin, Calif.
Rainfall in inches
30
20
10
0
Annual Run-off in acre-feet
300,000
200,000
100,000
0
Discharge of the Santa Ana River near Prado, Calif.

FIG. 3

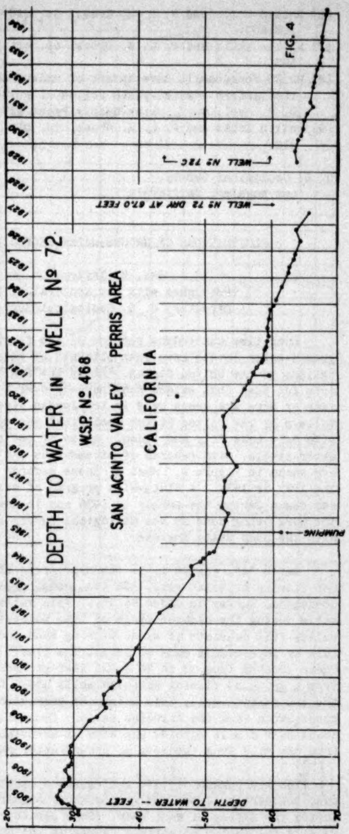
from surface-streams, of which the Santa Ana River is the largest, and by penetration of rainfall on a part of the area. In some sections, owing to impervious clay-strata, the rainfall cannot penetrate to the basin-gravel but remains near the surface as perched water and has to be drained away before the land is usable. The ground-waters are required for domestic and irrigation use.

The specific yield for the lower Santa Ana River Area ranges between four and 16 per cent and is lowest around the margin of the area. The storage-capacity for the zone 50 feet above and below the water-table of January 1933 is 492,000 acre-feet [9].

The J. B. Neff Well was destroyed in 1922. In 1926 measurements were begun at another well, which is considered a reliable companion for the Neff Well and which is also plotted on Figure 3. The general trend shown on this Figure indicates a general decline since 1917. The rainfall and runoff in 1922 probably caused considerable replenishment, but as this period is missing in the record, the rise is not known. In 1898 the water stood 113 feet above sea-level in the Neff Well. It then dropped to 84 feet in 1905, rose to 99 feet in 1908, reached another low of 65 feet in 1913, and rose during the next four years, reaching 100 feet in 1917. Except for a possible rise in 1922-23, the trend since 1917 has been definitely downward, until in 1935 the water in the companion well was only eight feet above sea-level. The declining water-level is causing grave concern to many of the residents of this district. The main source of replenishment--the flow of the Santa Ana River--has been decreasing since the record of stream-flow was started in 1919-20. Unless the flow of the Santa Ana River at Prado for the period of record has been much below the normal, a serious overdraft is indicated.

Well 72, in the San Jacinto Valley

The Perris Area is in the San Jacinto River Drainage-Basin, Riverside County. A discussion of the ground-water hydrology of this area is given in Water-Supply Paper 429, "Ground-water in the San Jacinto and Temecula basins, California," by G. A. Waring, 1919.



As indicated by the graph of water-levels in Well 72, shown on Figure 4, the demand on the ground-waters of this area has, with a few minor exceptions, exceeded replenishment. This failure of replenishment has caused the abandonment of many pumping plants and has returned to dry farming many tracts that were formerly irrigated.

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[3] W. C. Mendenhall, U. S. Geol. Surv. Water-Supply Papers 137, 138, 139, 142, and 225.
[4] Rollin Eckis and P. L. K. Gross, op. cit. under [1], pp. 146-149.
[5] Rollin Eckis and P. L. K. Gross, op. cit. under [1], p. 151; also W. C. Mendenhall, The hydrology of San Bernardino Valley, California, U. S. Geol. Surv. Water-Supply Paper 142, 1905.

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[7] Rollin Eckis and P. L. K. Gross, op. cit. under [1], p. 198.
[8] W. C. Mendenhall, Development of underground waters in the eastern coastal-plain region of southern California, U. S. Geol. Surv. Water-Supply Paper 137, p. 11, 1905.
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FLUCTUATIONS OF GROUND-WATER LEVELS IN UTAH

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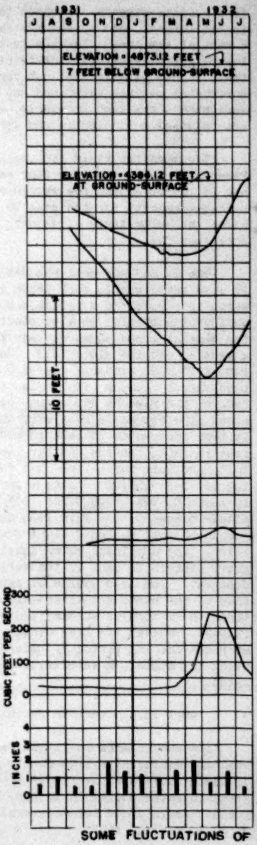
(Published with the approval of the
Director, U. S. Geological Survey)

Long-time continuous records of the fluctuations of ground-water levels have been obtained at relatively few locations in the United States. Among the few available records for Utah that extend continuously over a period of a year or more are those made in the Jordan River and Ogden valleys by the United States Geological Survey in cooperation with Salt Lake City and Ogden. A few of the records of water-levels, with records of stream-flow and precipitation, are shown in Figure 1. Most of these records were begun during 1931 or 1932. A State-wide program of well-observations was begun during the summer of 1935 and is now in progress, the work being done by the Geological Survey in cooperation with the Utah State Engineer.

Curve "A", Figure 1, is the hydrograpn of an 8-1/4 inch non-flowing artesian well, 108 feet deep, drilled by the Geological Survey in Ogden Valley. This valley was inundated during the highest stage of Lake Bonneville, and the valley-fill consists of water-bearing sand and gravel overlain by impermeable beds of lacustrine clay. The City of Ogden obtains from 13 to 20 cubic feet per second of water from a group of flowing artesian wells about two miles from the observation-well, this being the only withdrawal of any consequence from the artesian basin. The well is located about half a mile outside the area of artesian flow and less than one mile from the area of ground-water recharge.

The hydrograph of this well shows a distinct annual cycle, the period of maximum ground-water recharge beginning during the spring of each year. This period coincides closely with the period of maximum runoff in the streams entering Ogden Valley. The depressions in the curve during the summer and fall are caused chiefly by the withdrawal of water through the city wells. The curve shows clearly the sharp decline resulting from the drought and heavy ground-water withdrawals of 1933-34 and the rapid recovery in 1934-35. The hydrographic year of 1933-34 was very deficient in precipitation, especially at high altitudes, and the amount of ground-water recharge was consequently small. The exceptionally low stage reacned in the fall of 1934 was caused by the small amount of recharge during the spring and by increased withdrawals during the summer. The precipitation during the winter of 1934-35 was about normal and resulted in about normal discharge of the streams entering Ogden Valley and ample recharge to the ground-water reservoir. Because of the adequate precipitation and surface-runoff, heavy ground-water withdrawals by the City of Ogden did not begin until late in the summer of 1935. Consequently, the recovery in 1935 was greater in amount and continued over a longer time than in the two previous years, and the water-level in the observation-well was about as high during the summer of 1935 as at any time during tne period of record. During the fall of 1935 the points of outlet of the flowing wells were lowered about five feet, and the hydrograph of the observation-well indicates that



SOME FLUCTUATIONS OF

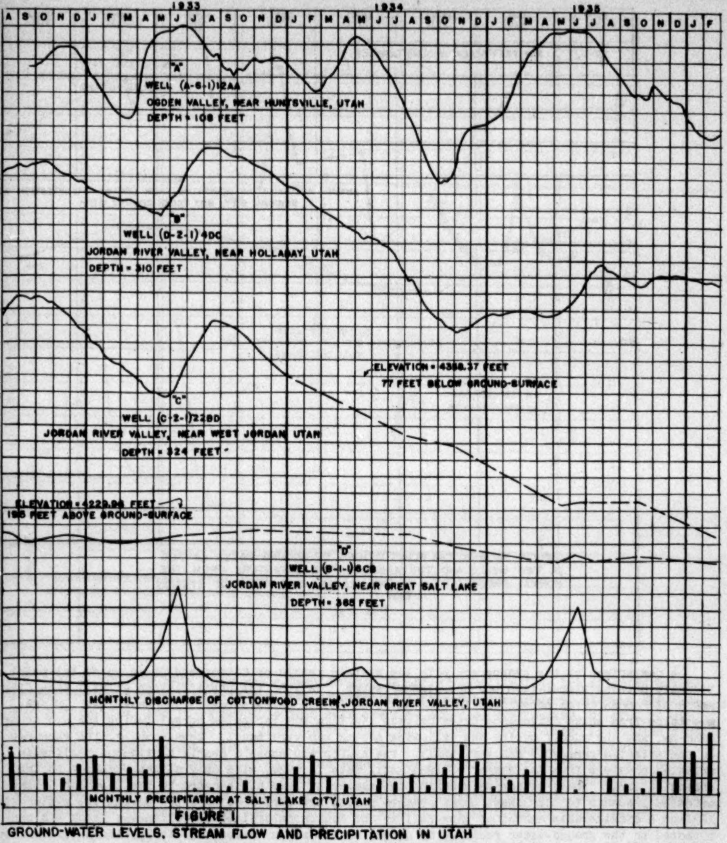


FIGURE I

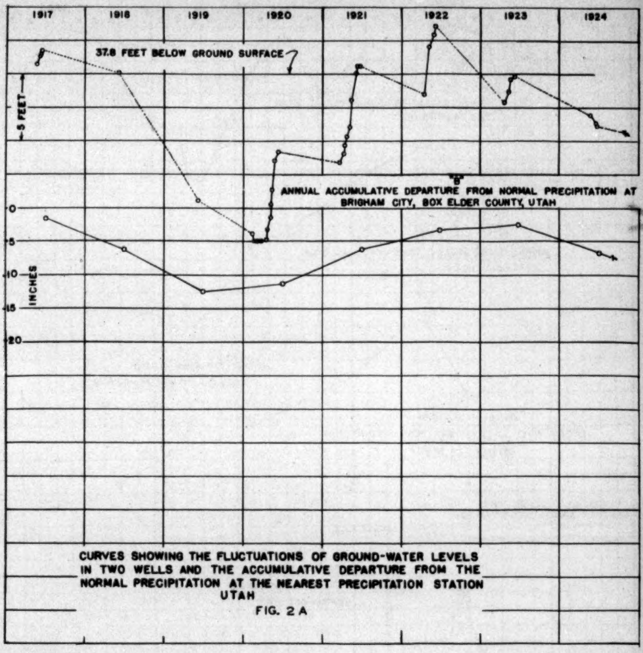
GROUND-WATER LEVELS, STREAM FLOW AND PRECIPITATION IN UTAH

the ground-water withdrawals were somewhat larger during the fall of 1935 than during the falls of previous years.

Figure 1 shows also hydrographs of three wells in the Jordan River Valley, the monthly discharge of Cottonwood Creek, and the monthly precipitation at Salt Lake City.

Curve "B", Figure 1, is the hydrograph of an artesian well that was drilled in 1923 in the vicinity of Cottonwood Creek, near the eastern edge of the area of artesian flow of the Jordan River Valley and a short distance below the recharge-area of the artesian basin. It flowed during only parts of 1932 and 1933 but is reported to have had a continuous flow in former years.

The hydrograph shows an annual cycle, which, however, was interrupted in 1934. The trend of the artesian pressure of the well was upward during 1932 and 1933, even though the precipitation during those years was below normal. This was probably due, in part, to recharge by seepage of irrigation-water derived from the mountain-streams that enter the Valley from the east.



CURVES SHOWING THE FLUCTUATIONS OF GROUND-WATER LEVELS IN TWO WELLS AND THE ACCUMULATIVE DEPARTURE FROM THE NORMAL PRECIPITATION AT THE NEAREST PRECIPITATION STATION UTAH

FIG. 2 A

A comparison of the hydrograph with the monthly record of Cottonwood Creek shows the relationship between stream-flow and artesian pressure. In 1933 the precipitation at Salt Lake City was 5.02 inches below normal and in 1934 was 1.84 inches below normal. The snow-cover in the mountains from which Cottonwood Creek derives its flow was far below normal during the winter of 1933-34, and the runoff during the following spring was very small. Consequently, the recharge to the artesian reservoir was very small. The hydrograph shows a nearly continuous decline in artesian pressure from the summer of 1933 until late in 1934, with only slight recharge in the spring of 1934. Heavy withdrawals during the summer of 1934 contributed to the lowering of the artesian pressure to the lowest point reached during the period of record. During the winter of 1934-35 a considerable amount of snow fell in the mountains drained by Cottonwood Creek and contributed to the ground-water recharge by direct runoff and by seepage of irrigation-water derived from the mountain snows. In 1935, however, the precipitation at Salt Lake City was 3.17 inches below normal and, because of the excessive dryness of the soil following the drought of 1934, the amount of water that reached the ground-water reservoir during the recharge-period of 1935 was relatively small. This is shown by the small amount and short period of recovery of the artesian pressure in the well during 1935 as compared with recharge during 1932 and 1933. However, the general trend between October 1934 and January 1936 was upward. Between January 1935 and January 1936 the water-level in the well rose about two feet.

The normal annual precipitation at Salt Lake City for a 62-year period is 16.13 inches. The precipitation during each year since 1927 has been below normal, the total deficiency between 1928 and 1935 amounting to 22.16 inches. The general upward trend of the water-level in the observation-well represented by curve "B" during years having less than normal precipitation indicates that the ground-water withdrawals in its vicinity do not exceed the recharge to the ground-water reservoir except during years of severe drought.

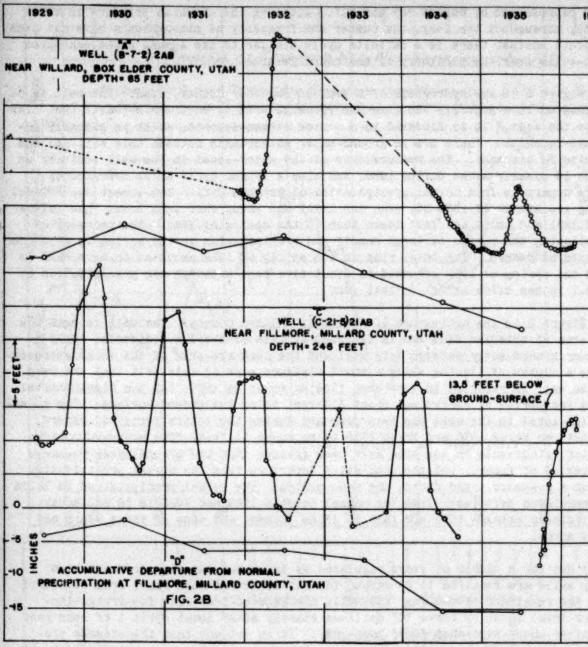


FIG. 2B

During 1932 and 1933 there was a considerable amount of overflow from the artesian basin through springs near the edge of the area of artesian flow and return-flow to streams crossing the recharge-area, and it is probable that some overflow occurred even during the drought of 1934. Therefore, to utilize this ground-water overflow, existing ground-water developments can be enlarged to some extent. Further developments will undoubtedly decrease the pressure and flow of existing wells, especially along the edge of the present area of artesian flow, but for the greatest benefit to the greatest number it is desirable to lower the ground-water levels in the intake-area by withdrawals from the artesian wells during times of need, thereby increasing the opportunity for recharge to the ground-water reservoir during times of excess water.

Curve "C", Figure 1, represents fluctuations of the water-surface in a well on the west side of the Jordan River Valley between the western recharge-area and the area of artesian flow. The opportunity for ground-water recharge from precipitation and stream- and irrigation-seepage is much less on the west side of the Valley than on the east side. Thus the general trend of the curve has been downward since the beginning of the record, which is believed to be due mainly to the lack of opportunity for recharge. The water-level represented by curve "C" has followed the deficiency in precipitation more closely than the level represented by curve "B". The withdrawals in the vicinity of the well represented by curve "C" were apparently in excess of the recharge in that area, although they were much less in quantity than in the vicinity of the well represented by curve "B".

Curve "D", Figure 1, represents the fluctuations of the artesian pressure in a well in the Jordan River Valley, near the edge of Great Salt Lake, about 13 miles northwest of the wells represented by curves "B" and "C". It is a flowing artesian well, finished in fine lake-sediments. A considerable amount of methane gas is discharged from the well with the water. The general direction of ground-water movement in the Jordan River Valley is toward this well and from the wells represented by curves "B" and "C". Although the artesian pressure in this well varies slightly throughout the year, the number and frequency of measurements have not been sufficient to indicate whether there is a definite cycle similar to the annual cycle exhibited by the observation-wells near the periphery of the recharge-area.

Curve "A" in Figure 2 is the hydrograph of a well in Boxelder County, Utah. The well is 65 feet deep and is located on a gravelly slope in the recharge-area of an artesian basin that lies a short distance to the west. It is finished in a coarse stream-deposit, which is probably intermingled with lake-deposits. There are no ground-water withdrawals between this well and the base of the mountains to the east. The measurements of the water-level in the well indicate an annual cycle, which is clearly shown during 1935, and also a longer cycle which corresponds with the cumulative departure from normal precipitation at Brigham City. The lowest water-level was recorded during the winter of 1934-35, when the level was about four feet lower than following the drought of 1931 and about one foot lower than in the spring of 1920. The recovery of the water-level following the period of large runoff and precipitation in the spring is shown for a number of the years of record. The total rise in the spring of 1932 amounted to more than 12 feet. The rise in the spring of 1935 amounted to about five feet although the precipitation at Brigham City was 4.1 inches below normal in that year.

Curve "C" in Figure 2 is the hydrograph of a well in Millard County. The well is near the east margin of an area of artesian flow and is finished in Lake Bonneville sediments. Only a few windmills recover ground-water between this well and the recharge-area of the artesian reservoir, but there are a number of flowing wells a short distance west of this well that are used for irrigation. The well is reported to have been flowing prior to 1927, but the highest level of the water during the period of record was about 3.0 feet below the ground-surface. The general trend of the water-level in the well has been downward during the entire period of record, the total decline between March 1930 and March 1936 being about 11 feet. The hydrograph shows that the ground-water withdrawals in the area have been greater than the ground-water recharge during the entire period of record, but the cumulative departure from the normal precipitation at Fillmore also has a downward trend during the same period. The normal precipitation is 14.34 inches, and the accumulated deficiency from the normal between 1929 and 1935 is 12.23 inches. The accumulated deficiency between 1931 and 1935 is 13.65 inches, and none of these years had precipitation above normal.

Millard County has for a number of years regulated by ordinance the flow from artesian wells. All flowing wells are required to be capped for six months of each year, from October 1 to April 1; during the remainder of the year the wells are allowed free flow for irrigation-purposes. The water-level shown by curve "C" declines sharply after about April 1 of each year and rises sharply after about September 30 of each year. It is evident that the effects produced by the operation of the flowing wells in the district mask the less pronounced effects of recharge and natural discharge.

Since 1917 the water-level in this well has been lowered more than 18 feet but the accumulated deficiency from the normal precipitation at Fillmore has been 12.9 inches. The water-level was only slightly lower in March 1934 than in March 1932, during which period the deficiency in precipitation was 1.5 inches. With normal precipitation, the recharge will probably nearly equal the present rate of withdrawal, and in successive years with more than normal precipitation the recharge may exceed the present rate of withdrawal, with a resulting increase of artesian pressure. It appears that caution should be used in making further developments of ground-water in this area, and the utmost efforts should be made to prevent any waste and to restrict the withdrawals from existing wells to necessary use.

U. S. Geological Survey,
Salt Lake City, Utah

THE UNDERGROUND WATER-INDEX: ITS RELATION TO SURFACE-RUNOFF

Caleb Mills Saville

Southern New England and especially Connecticut have recently experienced a remarkable antithesis in meteorological phenomena, the end of which cannot be recognized for some time to come. Reference is made to recent visitation of drought and flood following in quick succession. While flood and its effects are spectacular and receive prompt notice, drought-conditions usually are not so fully in the public mind, although their effects in the end may cause greater loss and inconvenience than do the most destructive floods in this part of the United States.

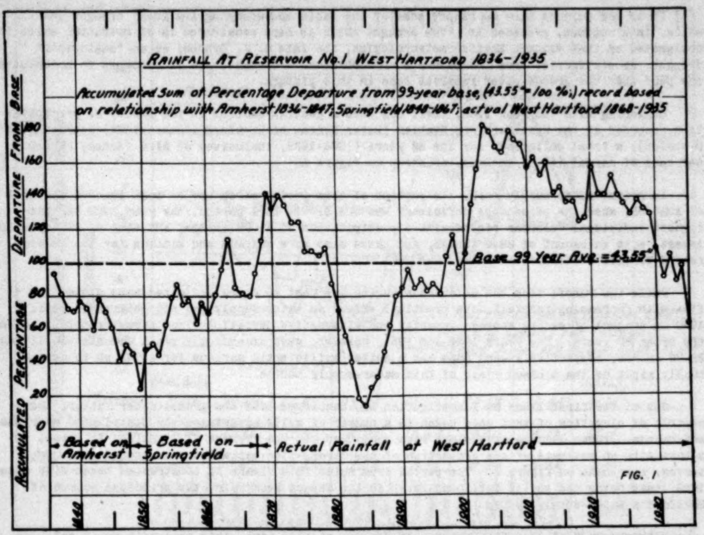

RAINFALL AT RESERVOIR No. 1 WEST HARTFORD 1836-1935
Accumulated Sum of Percentage Departure from 99-year base, (43.55" = 100 %;) record based on relationship with Amherst 1836-1847; Springfield 1848-1867; actual West Hartford 1868-1935
ACCUMULATED PERCENTAGE DEPARTURE FROM BASE
180
160
140
120
100
80
60
40
20
0
Base 99 Year Ave. = 43.55"
Based on Amherst
Based on Springfield
Actual Rainfall at West Hartford
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930

FIG. 1

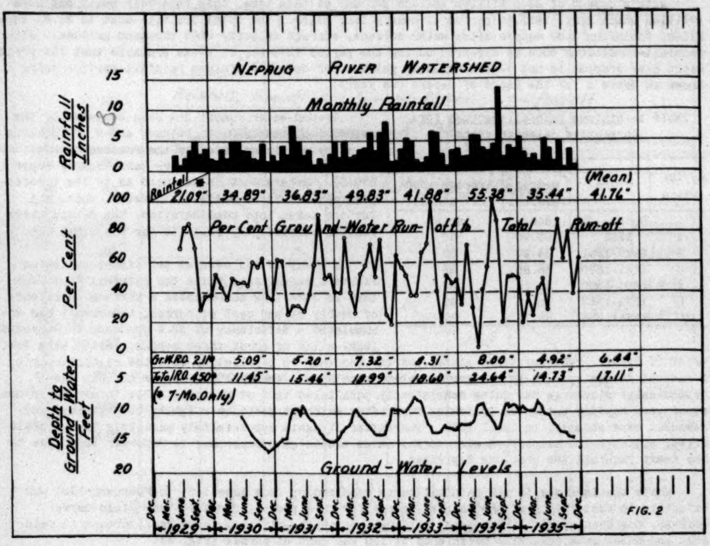

NEPAUG RIVER WATERSHED
Monthly Rainfall
Rainfall Inches
15
10
5
0
Rainfall
21.09"*
34.89"
36.83"
49.83"
41.88"
55.38"
35.44"
(Mean) 41.76"
Per Cent
100
80
60
40
20
0
Per Cent Ground-Water Run-off to Total Run-off
Gr.W.R.O. 2.11* 5.09" 6.20" 7.32" 8.31" 8.00" 4.92" 6.44"
Total R.O. 4.50* 11.45" 15.46" 18.99" 18.60" 24.64" 14.73" 17.11"
(* 7-Mo. Only)
Depth to Ground-Water Feet
5
10
15
20
Ground-Water Levels
Dec. Mar. June Sept.
1929
1930
1931
1932
1933
1934
1935

FIG. 2

It is the purpose here to record some of the facts accompanying the local drought and which, in a measure, preceded it. The drought which is here considered is of character which is designated by that eminent English meteorologist, the late G. J. Symons, as an "engineer's" drought, as distinctive from the farmer's or husbandman's drought, and it proposed to accentuate the part that the ground-water reserves take in this picture.

Beginning with the year 1903, there has been a general decline in the amount of precipitation recorded at the West Hartford Station [Water Bureau of Hartford (Connecticut) Metropolitan District], a total deficiency for the 32 years (1904-1935, inclusive) of 51.8 inches, or 119 per cent of normal (43.55 inches), as shown on Figure 1.

In recent water-supply work, the portion of this period which was of most concern was that of 1920-35, when the percentage deficiency was 113.6. In this period, the year 1920 had the highest individual calendar record with a precipitation of 56.95 inches, and that of 1935 was the lowest, with an amount of 28.9 inches, and these also were maximum and minimum for the 68-year record of this station.

While the runoff from the watersheds during the past 15 years indicated some diminution of flow with decreasing rainfall, the practical effect on water-supply was not noticeable until 1930 on account of excess storage-capacity and alternative deviations from normal rainfall during the prior 30 years. The years 1930 and 1931, however, gave exceedingly small amounts--34.11 and 35.76 inches, respectively--and this was a matter sufficiently serious for study as to what actually might be the minimum yield of this water-supply source.

One of the first lines of investigation was concerned with the ground-water factor, and records of elevation of that were begun in a number of wells advantageously distributed over the watersheds. These studies have since been continued and the average fluctuations in these, together with an estimate of the proportion of the stream-flow estimated from ground-water reserves, are shown on Figure 2. The period from which this Figure is constructed began with June 1929, that being the end of full pond-level in the Nepaug Reservoir, the principal source of Hartford's water-supply system.

With a demand of 23.5 million gallons per day at this time, this reservoir would not have refilled until April 1933, a period of nearly four years. The total drainage-area is 31.85 square miles, including 1.33 square miles water-surface, storage-capacity 9500 thousand gallons. With rainfall-conditions such as occurred during the period 1879-83, it seems probable that the yield might have dropped to not over 21 million gallons per day, the minimum rainfall-periods being shown in Table 1 for the years of record (68 years).

Table 1--Minimum rainfall-periods for consecutive calendar years

No. of years	Years	Average yearly rainfall	Percentage of average annual rainfall
		inches	inches
1	1935	28.90	67
2	1930-1931	34.94	80
3	1881-1883	35.86	83
4	1880-1883	36.12	83
5	1879-1883	35.72	82
10	1875-1884	38.74	89

Ground-water runoff has been computed by the method proposed by O. E. Meinzer and N. D. Stearns (A study of ground-water in the Pomeraug Basin, Connecticut, U. S. Geol. Surv. Water-Supply Paper 579-B). No argument is advanced as to its theoretical basis. It is believed, however, that, all factors taken into consideration, the method gives results sufficiently reliable for practical use.

A study of the several deficiency-curves on Figure 3 shows that, while the rainfall from June 1929 to June 1932 accumulated a maximum deficiency of nearly 38 per cent of normal, the runoff had accumulated a deficiency of 63.4 per cent to September 1932--a lag of about three months. After this low point in runoff, recovery takes place, and the tendency is parallelism with the rainfall-curve. A radical change appears in the ground-water trend about January 1933. Prior to this the ground-water discharge had quite consistently paralleled that of rainfall. The former curve now rises very rapidly until the following May, after which it declines slightly to September and, somewhat more steeply, to April 1934. Thereafter it again approximately parallels the rainfall-curve, although its comparison with normal shows excess-gain September to December 1934, due to the heavy rainfall the previous September.

While the long sag in the rainfall-curve down and up from June 1929 to February 1935 was effective in restoration of the rainfall-curve for this period, the long-term yield-curve, 1912-35, has been generally downward, although responding slightly to marked increase in rainfall and shows an accumulated deficiency of 150 per cent of normal (Fig. 4).

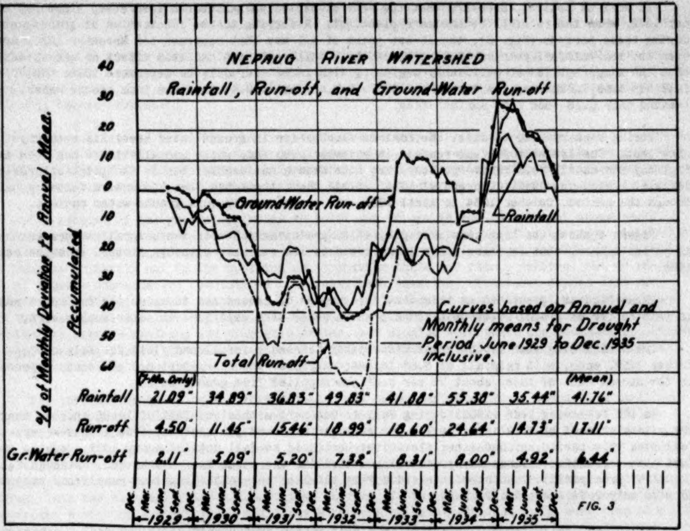

NEPAUG RIVER WATERSHED
Raintall, Run-off, and Ground-Water Run-off
%o of Monthly Deviation to Annual Mean.
Accumulated
40
30
20
10
0
10
20
30
40
50
60
Ground-Water Run-off
Raintall
Total Run-off
Curves based on Annual and Monthly means for Drought Period June 1929 to Dec. 1935 inclusive.
(7-Mo. Only)
(Mean)
Raintall 21.09" 34.89" 36.83" 49.83" 41.88" 55.30" 35.44" 41.76"
Run-off 4.50" 11.45" 15.46" 18.99" 18.60" 24.64" 14.73" 17.11"
Gr. Water Run-off 2.11" 5.09" 5.20" 7.32" 8.31" 8.00" 4.92" 6.44"
Dec. Mar. June Sept.
1929
1930
1931
1932
1933
1934
1935

FIG. 3

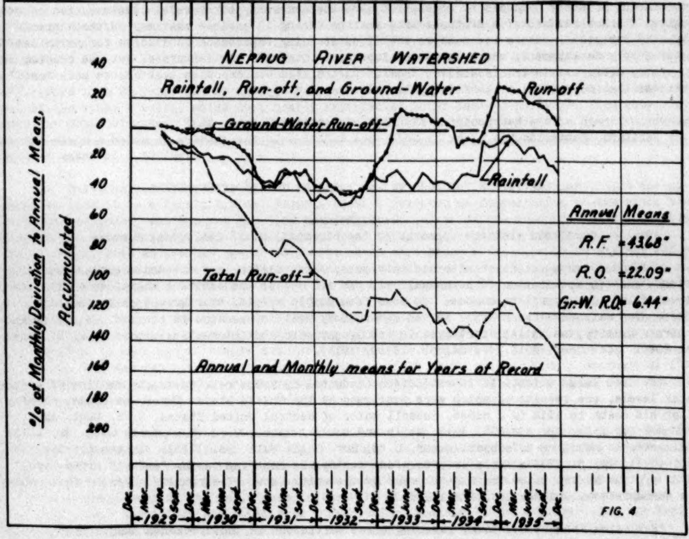

NEPAUG RIVER WATERSHED
Raintall, Run-off, and Ground-Water Run-off
%o of Monthly Deviation to Annual Mean,
Accumulated
40
20
0
20
40
60
80
100
120
140
160
180
200
Ground-Water Run-off
Raintall
Total Run-off
Annual Means
R.F. = 43.68"
R.O. = 22.09"
Gr.W. R.O. = 6.44"
Annual and Monthly means for Years of Record
Dec. Mar. June Sept.
1929
1930
1931
1932
1933
1934
1935

FIG. 4

It will be noticed, however, that the rate of depletion has become less steep since September 1932, when the rainfall became more plentiful. Referring to the fluctuation of ground-water during these periods (Fig. 2), the lowest point of all was that recorded for November 1930, and even the low-rainfall year of 1935, preceded by a full year, has had less effect on ground-water than the longer period of deficiency beginning with 1929. For July to September 1929, the rainfall was 6.68 inches and the runoff was 0.57 inch, of which 0.44 inch was from ground-water, leaving only 0.13 inch from surface-flow.

During January 1930 to date, the maximum fluctuation in ground-water level has been about nine feet. The lowest point was reached in November 1930 and, while annually there has been deficiency and nearly full recovery, there has also been a noticeable rise in the point of greatest deficiency each year until the end of 1934. Since then, there has been a downward tendency, although the period, October 1934 to April 1935, was one of nearly full ground-water content.

Figure 4 shows the long-term averages, which are coincident for the several factors in the graphical manner, that is, each curve is referred to its own base although plotted from the same line.

These data are presented at this time for purpose of record and to stimulate further study of this matter of ground-water relationship which seems very important in water-supply work.

One outstanding fact is the great discrepancy between rainfall and yield for July to September 1929, when, with rainfall of 6.68 inches, only 0.57 inch, or about 8.5 per cent, appeared in the stream and, of this, about 78 per cent was supplied from ground-water.

In the following year (1930) during July to October, with a rainfall of 10.85 inches, there was a total runoff of 0.79 inch, or 7.3 per cent, of which 53 per cent was from ground-water. Following this period, ground-water elevations continued to fall until January 1931, despite the fact that vegetative demands had practically ceased for the three last months and, although 6.14 inches of precipitation had been received during the last two months, surface-runoff had responded with only 0.74 inch runoff.

Two facts seem to stand out clearly upon this very casual presentation, namely, the tremendous amount of water demanded by vegetation, and the necessity for careful consideration of geological characteristics of a drainage-area in considering in advance what may be the ultimate capacity for yield. These two matters are of outstanding importance in studies for northeastern water-supply development, where large and important interests are concerned, but the problem is so vastly different in this so-called "humid" part of the country than that of the more "arid" portions that no general rules seem applicable.

The Water Bureau of the Metropolitan District of Hartford County,
Hartford, Connecticut

REVIEW OF THE WORK OF W J McGEE ON GROUND-WATER LEVELS

O. E. Meinzer

(Published with the approval of the Director, U. S. Geological Survey)

W J McGee was a scientist of broad interests, large vision, and unbounded enthusiasm for science and its application to human welfare. He was one of the earliest champions of the conservation of our natural resources. He rose from humble origin, by rigorous self-discipline, to outstanding national leadership. He was absorbed by zeal for service to mankind. His life had a heroic quality, as is well portrayed in the sympathetic and interesting memoir by F. H. Knowlton (Geol. Soc. Amer. Bull., v. 24, pp. 18-29, 1913).

The last large scientific investigation conducted by McGee related to the decline of ground-water levels, the results of which were published by the United States Bureau of Soils, chiefly after his death in 1912 (W J McGee, Subsoil water of central United States, U. S. Dept. Agri. Yearbook for 1911, pp. 479-490, 1912; Wells and subsoil-water, U. S. Bur. Soils Bull. 92, 1913; Field-records relating to subsoil-water, U. S. Bur. Soils Bull. 93, 1913). In the principal report (Bull. 92, p. 177) a table is presented showing the lowering in the "subsoil water-level" in 31 typical states since their settlement by the white race. The results given in that table are summarized as follows (pp. 178-179):

"Excluding Kansas, the total lowering since settlement as thus reckoned ranges from 2.3 feet in Florida and 3.1 in Nebraska to 17.1 in Pennsylvania, where the subsidence of the water is presumably in part due to mining and other industrial operations; yet it is 16.3 feet in Wisconsin, 14 feet or over in Indiana, Maryland, and Minnesota, and over 10 feet in 14 out of 31 typical states. . . . .

"In the 31 states forming the half of the country best adapted by natural conditions to feed and clothe a great people the average lowering since settlement would appear to be no less than nine feet. . . . . Its rate of lowering can only be regarded as a measure of advancing national impoverishment."

These conclusions have been widely quoted, and as they have been published in a bulletin of one of the scientific bureaus of the Federal Government, they have been and still are generally accepted as reliable and as indicating demonstrated progressive impoverishment in the water-supply of wells, springs, and streams, and in the soil-moisture available for food-production.

The purpose of the present paper is to point out errors in the fundamental assumptions of McGee's work which, it is believed, make the quantitative conclusions without value. This criticism must be regarded as an unpleasant duty, which cannot conscientiously be longer deferred. It relates primarily not to the question as to whether there has been a decline, but to the value of McGee's quantitative conclusions concerning this question. The three papers that have been cited contain numerous statements of large import, some of which are not definitely based on the results of the investigation. In the judgment of the present writer, some of these statements express profound and prophetic truths, but mingled with these are statements that are unsound and incorrect. The present paper is limited, however, to consideration of the fundamental assumptions underlying the quantitative conclusions.

The information on which the investigation was based was obtained by means of a questionnaire dated August 1, 1910, copies of which were mailed in September, 1910, to about 33,000 township crop-reporters of the Department of Agriculture. Nearly half of the reporters replied, and nearly a third of them sent in more or less carefully filled schedules, each covering from one to three or more wells. The records of 28,906 wells were tabulated by counties, including some wells in each of the 48 states. The wells were divided, according to rather complicated rules, into two classes, class A comprising, in general, the shallow wells that more or less represent water-table conditions, and class B comprising mainly drilled wells more than about 50 feet deep. The tabulation included 20,650 "bi-state wells," that is, wells for which the depth of water in the well was given for two dates, namely, the depth at the time the schedule was filled out and the original depth. Of the bi-state wells, 15,406 were assigned to class A and 5244 to class B. The records indicated that in 11,109 bi-state wells the depth of water had not changed, in 1401 it had increased, and in 8140 it had decreased. They indicated an average age of the wells, or average period between the dates for which depths of water were given, of a little more than 20 years and an average decrease in depth of 1.85 feet. They further indicated that of the class A wells, which most nearly represented water-table conditions, 7153 showed no change in depth of water, 1228 showed an increase, and 7025 showed a decrease. They indicated for the class A wells an average age of a little less than 25 years and an average decrease in depth of water of 1.67 feet.

The individual wells are listed for only one county--Newton County, Missouri, with the explanation that it is a fairly typical "county-sheet," selected as representing on the whole the best-reported county and one not far from the geographic center of the country. This sheet lists 40 wells for which original and "present" depths of water were reported. Of these, 31 were class A wells, with an average age of 30 years; seven were class B wells, with an average age of eight years; and two were not classified in the county-schedule but were apparently included with the class B wells in the State tabulation. Of the class A wells, 20 were reported to have had no change in depth of water and 11 were reported to have had decreases as follows: Fourteen feet in one well, 10 feet in one well, three feet in two wells, two feet in one well, 1.5 feet in one well, one foot in two wells, and half a foot in three wells. Of the seven class B wells, six were reported to have had no change and one to have had a decrease of 10 feet. Of the unclassified wells, one was reported to have had an increase of 10 feet and the other a decrease of five feet. These figures give an average decrease of 1.2 feet for the 31 class A wells and 1.4 feet for the seven class B wells.

In the further computations the basic assumptions were made (1) that changes in the depths of water in the wells were caused entirely by changes in the level of the water-table, which in McGee's report is also called the "subsoil water-level" and the "ground-level of water," and (2) that the average decline in the water-table had progressed in each State at a constant rate from the time of settlement by the white race to the fall of 1910, when the schedules were filled out. The second assumption was considered conservative, because it was believed that the most rapid decline occurred soon after settlement and largely prior to the periods covered by the well-records.

The first of the two basic assumptions took no account of the filling of the wells by caving or introduction of material from the outside. Obviously one reason for asking for the depth of water rather than the depth to the water-level was the uncertainty that would exist in many wells as to the levels from which the original depths to water might have been measured. There is no basis for estimating the amount of filling that may have occurred in the average period of about 20 years, but it was almost certainly a considerable part of the 1.85 feet that was computed as the average decrease in depth of water. In remeasuring the depth of old wells it is very commonly found that the measured depth is somewhat less than the reported original depth. The discrepancies are probably due chiefly to caving and filling but doubtless in part to somewhat exaggerated depths reported by certain drillers who worked on a footage basis. Of the 31 class A wells in Newton County, Missouri, with an average decrease of 1.2 feet in depth of water, the two wells with decreases of 14 feet and 10 feet may reasonably be suspected of having caved. If these two wells were excluded from the computation, the average decrease in depth of water would have been only 0.4 foot instead of 1.2 feet. Likewise, the report that six of the seven class B wells in Newton County showed no change and the other showed a decrease of 10 feet suggests a special explanation for this well, such as caving.

The method of computing the total decline of the water-table to 1910 in each State can be illustrated by the computations for Virginia, which showed a nearly average decline. There were in Virginia 602 class A wells, with an average age of 30.1 years, of which 301 wells showed no change, 31 showed an increase, and 270 showed a decrease. The 602 wells showed an average decrease in depth of water of 1.2 feet. This was taken to be a rate of decline of 0.384 foot per decade. Likewise, of 58 class B wells, with an average age of 7.3 years, 41 were reported with no change, one with increase, and 16 with decrease, giving an average decrease of 2.94 feet, or a computed decline of 4.027 feet per decade. It was then computed that the weighted average decline for the wells of both classes was 0.725 foot per decade, or 8.7 feet for the period of 120 years since settlement.

The assumption that decline in water-levels has progressed at a constant rate has been demonstrated to be entirely erroneous. In most places in the humid and subhumid parts of the country there is a pronounced annual fluctuation of the water-table. As a rule the water-table stands highest in the spring, is greatly lowered during the growing season, and recovers during the dormant season. This annual period of recharge and recovery may begin in the late fall, or during the winter, or not until spring. In the less humid areas there may be years in which there is no recovery. In the northern parts of the country the ground may be frozen throughout the winter and the recovery may occur at the time of the spring break-up, when there may be heavy recharge within a short period. In years with exceptionally heavy rains in summer, as in Virginia in 1928 and 1934, and in parts of the Mississippi River Basin in 1935, this normal annual cycle is radically modified by heavy recharge in summer. On the other hand, in dry years there may be progressive decline from late spring throughout the summer, fall, and winter. In such years the decline is generally most rapid in late summer and early fall, with the result that by September or October the water-table stands considerably below the average stage for these months. If there is a series of dry years, such as culminated in a large part of the country in 1934, the stages in autumn are likely to become progressively lower and to reach extremely low levels in the autumn or winter of the culminating year.

It is significant that the McGee schedules were sent out in September 1910, and that most of the replies were received within a few weeks, that is, at the time of the year when the water-table is normally at or near its lowest stage.

It is moreover, significant that for much of the country 1910 was an exceptionally dry year. The compilation, by W. G. Hoyt, of the records for the Mississippi River Basin above Keokuk since 1878 shows that in 1910 the precipitation was lower than in any other year in the 33-year period from 1878 to 1910. The annual report of the Weather Bureau contains a map which shows that in 1910 the temperature was above normal in practically all parts of the United States and another map which shows that from March 1 to September 30, 1910, the precipitation was below normal in practically all parts of the country except Missouri, Arkansas, Kentucky, West Virginia, and the eastern parts of Virginia and North Carolina. The annual summary for 1910 indicates that, although the conditions were variable, it was essentially a year of drought from beginning to end, with severe drought in some parts of the country, especially in a large part of the interior. The year had some of the features of 1934, although the conditions were not nearly so extreme and there was no comparable culmination of a period of dry years.

In Bulletin 92 (pp. 164-165) the following statements are made concerning the relation of precipitation to water-levels:

"A good many remarks bring out the sequential relation between rainfall (or its dearth) and both the level and amount of water in the ground, and while this interdependence is doubtless in some cases overestimated, a general review of the remarks and records would seem to indicate that a part of the lowering of water-level shown in the tables should be ascribed to exceptional droughts, for example, probably to the extent of a few hundredths of a foot in Minnesota and perhaps a few tenths in eastern Texas and Oklahoma. . . .

"Notably a few of the utterances are pessimistic, not many look to continuation of the current trend; most imply a special or temporary reason for the growing dearth of water in exceptionally limited rainfall or other cause."

In the computations published in Bulletin 92 no allowance was made for temporary lowering of the water-levels.

The considerable amount of exact water-level information that is now available is ample to show that the seasonal and cyclic fluctuations of the water-table are of such an order of magnitude that they could account for all of the average decrease in depth of water reported in the McGee schedules, at least in the class A, or essentially water-table wells. The average decrease reported in these wells was 1.67 feet for all states, with a maximum of 3.87 feet for Minnesota. The following compilation of data, based on measurements made by the United States Geological Survey and cooperating agencies, shows the general magnitude of seasonal and cyclic fluctuations of the water-table. The wells of the several groups in which the periodic measurements used in the compilation were made are all or nearly all essentially water-table wells. Most of them are shallow-dug wells, though some in Nebraska and Wisconsin are more than 100 feet deep. All the wells are believed to be in localities that are not materially affected by pumping, and nearly all, except those of the Connecticut and New Jersey groups, are unused wells that are maintained as observation-wells.

The exact data now available make it clear not only that McGee's very pessimistic conclusions were not warranted but also that the ground-water conditions are vastly more complex than was understood in his time. As a pioneer, however, he undoubtedly rendered a large service in calling attention to the ground-water as a natural resource, to the public duty of taking proper steps for its conservation, and to the basic need for systematic records of its depletion and replenishment. There is no longer any excuse for haphazard development, overdevelopment, and waste of the ground-water supplies. With a systematic program of periodic water-level measurements in properly selected observation-wells and adequate provision for the study of the resulting records, it will be possible to ascertain at any time in the future the exact stage of the water-table. Moreover, it will be possible to determine the quantities of water perennially available from the many diverse underground reservoirs from which our supplies are drawn, to detect long-term trends toward depletion on account of overdevelopment, waste, or other causes, and to lay a reliable foundation for the maximum beneficial use of the ground-water supplies, not for a limited period of years but perennially secure.

Table 1--Summary of the average fluctuations of the water-levels in groups of observation-wells in several states: Wells in which periodic measurements have been made for several years

State	Number of wells	Period	Average fluctuation in the period	Average annual fluctuation	Date of highest stage	Date of lowest stage
			ft	ft		
Connecticut	22	1913-16	5.3	3.7	Apr. 1916	Oct. 1913
Nebraska[a]	41	1931-35	3.01	1.35	Apr. 1931	Oct. 1934
New Jersey:						
Less than 25 feet deep	25	1923-35	7.00	....	May 1933	Sept. 1932
From 25 to 48 feet deep	6	1923-35	6.79	....	Aug. 1928	Oct. 1932
Pennsylvania	33	1931-35	5.56	4.52	Apr. 1933	Sept. 1932
Virginia	3	1931-35	12.56	5.15	Apr. 1935	Dec. 1931

[a] Based on quarterly records.

Table 2--Summary of the average fluctuations of the water-levels in groups of observation-wells in several states: Wells in which periodic measurements have been made since some time in 1934[a]

[The water-levels in all wells were reduced to arbitrary datum-planes, the datum in each well being 10 feet below the water-level on January 1, 1935]

State	Number of wells	October 1, 1934	April 1, 1935	October 1, 1935	January 1, 1936	Average fluctuation in period 1934-35[b]
		ft	ft	ft	ft	ft
Iowa and Missouri	15	9.09	10.55	11.48	11.62	4.76
Kansas	24	10.27	9.94	12.25	13.35	3.64
Nebraska	252	9.54	10.26	10.17	10.36	1.36
North Carolina	21	....	12.60	9.01	11.90	4.44
Oklahoma	12	9.68	10.49	9.56	9.43	2.51
South Carolina	14	10.95	10.92	10.96	.....	1.56
Texas	16	9.35	11.68	13.31	15.19[c]	6.64
Washington	22	8.60[d]	13.69	7.64	9.06	6.08
Wisconsin	14	9.99	11.67	10.55	10.31	2.31

[a] All except the Nebraska wells are on experimental areas of the United States Soil Conservation Service; the measurements were made on or near the dates indicated.

[b] Except in Nebraska, measurements were generally made weekly, but only monthly measurements were used in this tabulation; therefore, the average fluctuations may actually be somewhat greater than indicated.

[c] December 18, 1935; no record yet available for January 1, 1936.

[d] November 1, 1934; no record available for October 1, 1934.

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PAPERS

THE SEEPAGE OF WATER THROUGH POROUS MEDIA UNDER THE ACTION OF GRAVITY

Morris Muskat

Until very recently the theoretical basis of the study of the flow of water through sands under the action of gravity remained the same as that formulated by J. Dupuit in 1863 [see 1 of "References" at end of paper]. This investigator, in attempting to derive an expression for the water-seepage into a well and the shape of the free surface within the sand body, based his analysis upon two fundamental assumptions, namely: (1) That the fluid moves towards the well-surface in vertical shells so that the horizontal component of the velocity is independent of the depth, and (2) that the magnitude of this horizontal velocity is proportional to the slope of the free surface. These two assumptions directly led to the results that the seepage-flux into a well of radius r_w in which the fluid-head is h_w, is

$$\overline{Q} = \pi k\gamma g(h_e^2 - h_w^2)/\mu \log(r_e/r_w) \tag{1}$$

where h_e is the fluid-height in the sand at a distant radius r_e, γ is the density of the water, g is the acceleration of gravity, k is the permeability of the sand, and μ is the viscosity of the water. The shape of the free surface in the sand is, by the same assumptions, determined by the equation

$$h^2 = [(h_e^2 - h_w^2)\log(r/r_w)/\log(r_e/r_w)] + h_w^2 \tag{2}$$

In 1886 P. Forchheimer [2] generalized these considerations, and on the basis of the same assumptions showed that for any gravity-flow system the height of the free surface h(x,y) would satisfy the equation

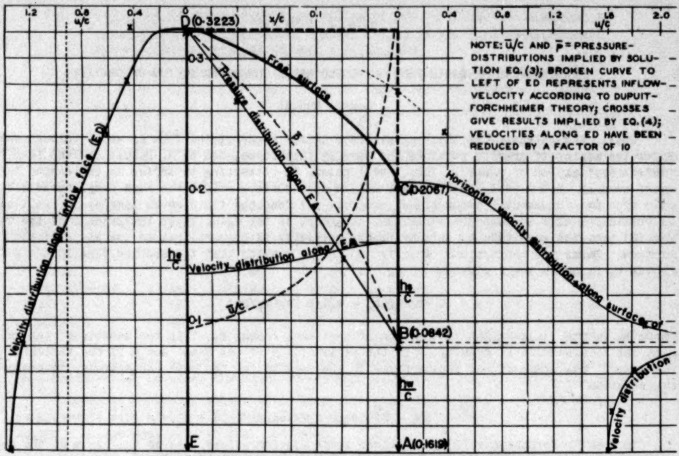
$$(\partial^2 h^2/\partial x^2) + (\partial^2 h^2/\partial y^2) = 0 \tag{3}$$

the procedure for determining the associated flux simply being that of computing the slopes of the free surface at the outflow-faces as obtained by the solution of this equation and multiplying by $(h_w k\gamma g/\mu)$. These results, especially in the hands of Forchheimer, have been applied to a variety of specific problems without any critical discussion of the validity of the assumptions upon which they were based.

Kozeny's [3] theory of 1927 does represent a more rigorous approach to the problem, but the assumptions subsequently made during the course of the analysis effectively vitiated the results. His own experiments and those of Ehrenberger [4], performed as a test upon his theory, led to inconclusive results, as they showed the necessity of introducing a purely empirical factor into the Kozeny formula in order to make them fit the observed data.

The later experiments of Wyckoff, Botset, and Muskat [5] with radial sand-models showed again that Kozeny's formula was incorrect, and that on the contrary the original Dupuit expression for the flux was accurate to within experimental errors. These authors recognized the fundamental weaknesses of the Dupuit assumptions, and in particular stressed the failure of that theory to take into account the fact that the free surface issues from the sand and into the well-bore at a height above the fluid-level in the well-bore. Furthermore, the failure of the Dupuit theory to give any consideration to the existence of vertical velocities within the sand-body, whose reality was confirmed not only by general theoretical considerations but also by the empirical observations, made the paradoxical situation whereby the flux predicted by such an erroneous theory was nevertheless correct, seem still more puzzling.

This situation was brought to a head by the fundamental work of Hamel [6], who in 1934 gave the first rigorous solution of the problem of the gravity-seepage of a liquid through a sand, wherein the "surface of seepage" lying between the fluid-head at the outflow-surface and the points of issuance of the free surface was explicitly taken into account. A detailed numerical application [7] of this theory to the simple case of the gravity-seepage through a dam with vertical faces showed clearly the erroneous character of the Dupuit assumptions. In particular, the shape of the free surface so computed differed widely from that given by the solution of equation (3), and the velocities along the inflow- and outflow-faces were definitely far from uniform and showed no particular relation to the slope of the free surface. This may be seen from Figure 1, in which the significant features of the flow-system for a particular case as computed from the exact analysis and as implied by the Dupuit-Forchheimer theory are indicated, those of the latter being represented by the broken curves. It will be clear from this Figure



NOTE: ū/c AND p̄ = PRESSURE-DISTRIBUTIONS IMPLIED BY SOLUTION EQ. (3); BROKEN CURVE TO LEFT OF ED REPRESENTS INFLOW-VELOCITY ACCORDING TO DUPUIT-FORCHHEIMER THEORY; CROSSES GIVE RESULTS IMPLIED BY EQ. (4); VELOCITIES ALONG ED HAVE BEEN REDUCED BY A FACTOR OF 10

FIG. 1—THE FREE SURFACE, VELOCITY, AND PRESSURE-DISTRIBUTION FOR A DAM WITH VERTICAL

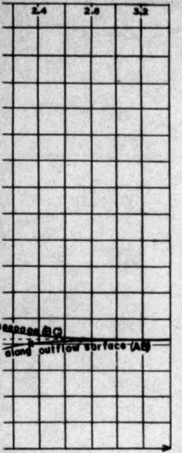
that, with respect to the details of the flow, the Dupuit-Forchheimer theory does not even give an approximation to that which actually takes place. Nevertheless, the paradox still remains that the seepage-flux through the dam, as calculated rigorously, agrees exactly, for all practical purposes, with that given by the otherwise completely erroneous Dupuit-Forchheimer theory, as is seen in Table 1, where h_e, h_w are the inflow and outflow fluid-heads, h_s is the length (computed) of the "surface of seepage" BC, L is the width of the dam, Q is the flux given by the rigorous calculations, and $\overline{Q}$ is that by the Dupuit-Forchheimer theory or the theory discussed below, that is, equation (5).

Table 1--The seepage-flux through dams with vertical faces

Case	I	II	III	IV	V	VI
h_e/c	0.322	0.670	0.672	0.872	1.286	1.823
h_w/c	0.084	0.158	0.000	0.000	0.000	0.000
h_s/c	0.122	0.202	0.430	0.519	0.646	0.719
L/c	0.162	0.444	0.329	0.484	0.906	1.692
Q/c^2	0.299	0.480	0.687	0.783	0.913	0.983
$\overline{Q}/c^2$	0.298	0.477	0.686	0.786	0.913	0.982

The resolution of this paradox obviously means that the flux-formulas as given by the Dupuit-Forchheimer theory are not to be uniquely associated with that theory, but must be considered as accidental consequences of it. And indeed this may be shown to be the case, as will be seen presently. For it is definitely possible to give an entirely different derivation of these formulas based upon a physical picture that has but little resemblance to that proposed by Dupuit-Forchheimer, and which should, from physical considerations, be expected to give values for the seepage-flux that are accurate to a high degree.

Such a theory may be based upon the replacement of the actual gravity-flow system by one with the same boundary-conditions but without the free surface. Thus in the case of the linear flow through a dam with vertical faces with inflow-head h_e and outflow-head h_w, the approximation system replacing the physical gravity-flow system ABCDE, will be AFDE with the same boundary-conditions along AF and ED, as in ABCDE. The boundaries EA and DF will be taken as impermeable. As the potential along CF rises continuously to equal, at F, the value along ED, it is clear that the total flux along CF will be small, so that the region DCF which does not occur in the physical gravity-flow system will contribute but little additional flux beyond that passing through the latter. (The term "potential" used here represents the fundamental physical variable determining the flow in systems in which gravity plays a significant role; it may be defined by $\Phi = (k/\mu)(p + \gamma g y)$, where p is the fluid-pressure.) Hence, although the flux through AFDE will necessarily exceed that through ABCDE, it is reasonable to expect that this excess will be of no practical significance, so that the former will give a very close approximation to the latter. Although this may be also directly confirmed by electrical model experiments, we shall see that



FACES

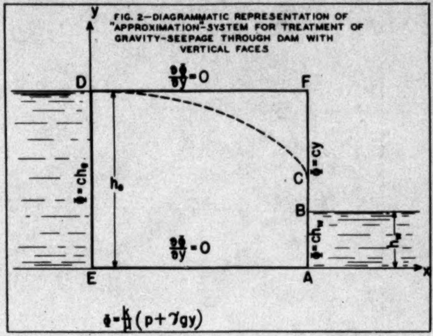


FIG. 2—DIAGRAMMATIC REPRESENTATION OF "APPROXIMATION"-SYSTEM FOR TREATMENT OF GRAVITY-SEEPAGE THROUGH DAM WITH VERTICAL FACES

y
D
F
$\frac{\partial\Phi}{\partial y}=0$
$\Phi=ch_e$
h_e
$\Phi=cy$
C
B
$\Phi=ch_w$
h_w
$\frac{\partial\Phi}{\partial y}=0$
E
A
x
$\Phi=\frac{k}{\mu}(p+\gamma gy)$

this is still more directly verified by the theoretical calculations.

Thus with the boundary-conditions along AF and ED as indicated in Figure 2, it may be shown that the potential distribution within the system AFDE is given by

$$\Phi = ch_e - (c/2h_eL)(h_e^2 - h_w^2)x$$
$$+ (2ch_e/\pi^2)\sum_1^{\infty}\left\{[(-1)^n - \cos(n\pi h_w/h_e)]/n^2 \sinh(n\pi L/h_e)\right\}\cos(n\pi y/h_e)\sinh(n\pi x/h_e) \qquad (4)$$

where c = kγg/μ. The associated flux is readily given by

$$\bar{Q} = -\int_0^{h_e}(\partial\Phi/\partial x)dy = c(h_e^2 - h_w^2)/2L \qquad (5)$$

which is identical with that following from the Dupuit-Forchheimer theory and which, as has been seen from Table 1, agrees for all practical purposes with that given by a rigorous solution to the problem.

That equation (5) is not also a fortuitous consequence of the present analysis, as it undoubtedly is in the case of the Dupuit-Forchheimer theory, is shown by the fact that it gives in addition a close reproduction of the pressure-distribution at the base of the system ACDE and of the inflow-velocities along the face ED and even along the outflow-face AC, except near the terminal C of the free surface. This will be clear from Figure 1, where the crosses give the values of the pressures and velocities corresponding to equation (4). The broken curves give the corresponding distributions following from the Dupuit-Forchheimer theory. Of course, the properties of the free surface itself are beyond the scope of this approximation-theory, but it does provide a rational explanation for, and gives the physical significance of, the formulas for the flux such as equations (1) and (5).

The same method may be applied to the problem of more practical interest of the seepage into a well, discussed at the beginning of this paper. For again replacing the physical gravity-flow system by one with identically tne same boundary-conditions while disregarding the existence of the free surface, one obtains for the internal potential-distribution the expression

$$\Phi = ch_e + \frac{c(h_e^2 - h_w^2)\log(r/r_e)}{2h_e\log(r_e/r_w)} + \frac{2ch_e}{\pi 2}\sum_1^{\infty}\frac{\left\{(-1)^n - \cos(n\pi h_w/h_e)\right\}U(\alpha_n r)\cos(n\pi y/h_e)}{n^2\,U(\alpha_n r_w)} \qquad (6)$$

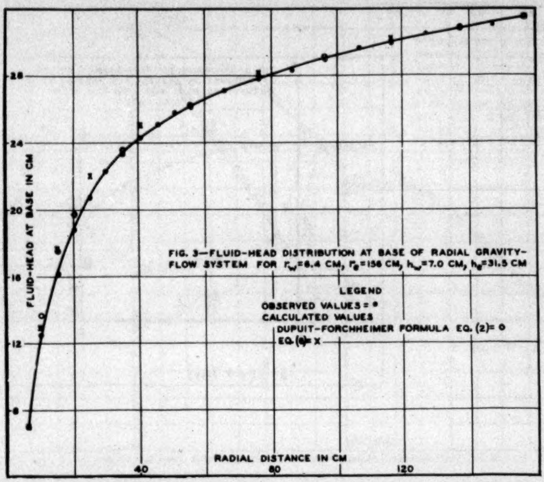


FIG. 3—FLUID-HEAD DISTRIBUTION AT BASE OF RADIAL GRAVITY-FLOW SYSTEM FOR r_w=6.4 CM, r_e=156 CM, h_w=7.0 CM, h_e=31.5 CM

where $U(\alpha_n r) = I_0(n\pi r/h_e)K_0(n\pi r_e/h_e) - I_0(n\pi r_e/h_e)K_0(n\pi r/h_e)$, I_0 and K_0 are the two fundamental Bessel functions of the third kind of zero-order, and the rest of the notation is the same as that in equation (1). The associated flux here again may be readily shown to be given by the original Dupuit formula of equation (1). Hence, as the latter has been found empirically to reproduce quite accurately the values in actual sand-models, the present theory also succeeds in this respect. But in addition it again gives a close reproduction of the pressure-distribution at the base of the radial-flow system as determined empirically [5], as is shown in Figure 3. While the circles calculated by equation (2) show perhaps an even better agreement with the empirical data, it must be remembered that according to the Dupuit-Forchheimer theory equation (2) should define the shape of the free surface which, however, differs markedly from the curves of Figure 3. Although no empirical data are available as to the velocity-distribution along the radial boundaries of the radial-flow system, we may safely anticipate that these would also be very closely approximated by the values derived from equation (6).

Finally, it may be observed that from the point of view of computing the flux through a gravity-flow system, one may even avoid the detailed analysis for the potential distribution within the flow-system of the approximation-theory, and simply use the ordinary flux-formulas for non-gravity flow-systems with the same average value of the potential difference across the boundaries. Thus it may be shown that the average of the potential over an outflow-surface which is covered hydrostatically by a liquid to a height h_w and which is exposed to the atmospheric pressure from there to the total height h_e, is given by $\bar{\Phi}_w = c(h_e^2 + h_w^2)/2h_e$. As the potential over the inflow-surface which is exposed hydrostatically to a liquid over the whole height h_e is ch_e, the difference of the average potentials is

$$\Delta\bar{\Phi} = c(h_e^2 - h_w^2)/2h_e \tag{7}$$

Applying this value to the ordinary flux-formulas in non-gravity flow-systems, in which the flux through the system is given for a unit-potential drop, all the formulas that would be implied either by the Dupuit-Forchheimer theory or that presented here will be obtained immediately. Furthermore, this procedure may be applied to composite gravity-flow systems where the fluid-head at the inflow-face may exceed the sand-thickness. For, if the latter be denoted by h_s and the liquid-head at the external boundary is $h_0 (> h_s)$, the corresponding average potential drop may be readily shown to be

$$\Delta\bar{\Phi} = c(2h_s h_0 - h_s^2 - h_w^2)/2h_s \tag{8}$$

Applying this also to the ordinary non-gravity flow-formulas, the correct values for the flux are obtained, as verified empirically.

The author wishes to thank Dr. P. D. Foote, Executive Vice-President of the Gulf Research and Development Corporation for the permission to publish this paper.

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HISTORICAL DEVELOPMENT OF IDEAS REGARDING THE ORIGIN OF SPRINGS AND GROUND-WATER

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The origin of water has been the subject of speculation ever since the formulation of tradition and myths regarding the creation of the world. But at the very beginning of Greek philosophy speculation turned from water, as one of the four elements, to the origin of springs.

Priests, poets, philosophers, naturalists, and engineers took up the subject in somewhat the order named. Then came the specialized scientists--astronomers, geographers, meteorologists, and hydrological engineers. From time to time the encyclopedists include springs in their grand summaries of all knowledge. The gross result has been an enormous mass of writing on the origin of springs. The net result has been a small body of well-considered theory, supplemented now and then with data and deductions. Of the 50 to 100 men who have written at some length on the subject, the utterances of a large percentage of the more significant or entertaining have been gathered and examined by one or other author of these notes, going back to original sources where libraries and time made that possible--translations in the case of classics and some other authors. Of the 60,000 words of source-material thus far amassed, only a small portion, and that chiefly by summary, can be given within the limits of this paper. Later it is hoped that much, if not all, the source-material, with critical comment, can somewhere be published.

By way of preliminary summary it may be stated that beside the now well-known and almost universally accepted pluvial origin of springs--the evaporation-condensation-precipitation-percolation cycle--there persisted from the earliest times until well into the nineteenth century, the ocean-fed theory. The latter was upheld by two schools: One, and the more general, believed that water passed from the ocean through subterranean channels and up to the surface of the Earth. The other believed that, instead of flowing through a few large channels, it percolated through an infinitude of small ones between layers of sand or other permeable material. In either case the water rose to the tops of hills and mountains. Many and various were the attempts to explain what lifted the water to such great heights and what became of its saltness. As to the motive power, some thought the water was vaporized and lifted by the internal heat of the Earth; others held that it went up by capillary action; still others that water circulated like sap in a tree or blood in man; others said that the motive force was the stars or the tides. As to what became of the salt, the first school held that it was deposited in the caverns and the second in the interstices of the Earth, both schools alike not troubling to tell why these did not fill up, or else offering fanciful explanations.

Broadly, the theories of the origin of springs followed one or another cosmogany, either the Hebrew creation by fiat or some one of the rational doctrines of the Greek philosophers who consider water as one of the four elements and go back of that to the "seeds" of "first beginnings" or atoms.

The seventeenth and eighteenth centuries were prolific with theories of the origin of springs. A large percentage of these were presented in sermons, essays, and books written to show the goodness of God and to uphold Creation by Design. Some of these combined the Hebrew and Greek cosmologies so far as to identify the Tartarus of Homer and Plato with the Great Abyss of Moses.

Abstract conceptions rather than observed facts were the basis of most of the theories for more than 1500 years. Some of these were illuminated by the lights of both reason and nature. Where natural phenomena were observed, they were limited and local. When of broader geographical range, vague reports were accepted and wrongly interpreted. This was truer in the earlier than the later centuries, but dogma often blinded reason even into the nineteenth century.

Although the pluvial origin of rivers was announced by Aristotle and accepted by many from that time on, yet more than a millenium passed before rainfall- and runoff-data to support this theory were accumulated and published or even such simple field-observations were made and recorded as tracing streams to their minute and multifarious sources in springs and mere oozes of moisture. A glimmering of the importance of elevated, exposed, pervious, water-receiving strata and accompanying impervious strata was seen and noted by the architect-engineer Vitruvius just before the birth of Christ. Its significance was almost or quite ignored until comparatively recent times. It was not until near the close of the eighteenth century that what became known as the Strattonian theory of stratification was announced. This pointed the way to an understanding of the origin not only of springs but of all underground waters.

Before taking up specifically some of the theories of the origin of springs a few words may be said about comprehensive reviews of the subject that have been written in the past. The first of these was by Seneca, at the close of the classical period (about 60 A.D.). In the eighteenth, nineteenth, and twentieth centuries, four pluvialists and one believer in the ocean-fed theory reviewed the subject. Of the pluvialists, all were engineers--three French and one a German. These men and the dates of their publications were: Perrault, 1674; Switzer (English), 1729; Arago, 1835; Dumas, 1856; Keilhack, 1912. The dates of two of the books are deceptive in so far as their reviews of the opinions of their predecessors are concerned, for both Dumas and Keilhack base their reviews of the opinions of others on Perrault. Dumas surveys three other later opinions, besides having a chapter in which he essays to review the theory in a complete manner. In these four reviews the original language of the several earlier writers is seldom given, and then generally in fragments.

Thales, one of the earliest and most notable of the Greek philosophers (6th century B.C.), left no writings. Diogones Laertes, to whom we are indebted for fragments and three letters of Thales, reports nothing by Thales on springs. Keilhack says that Thales "was of the opinion that the water of springs and streams is derived from the sea--driven out--into the Earth by the wind and when once in the Earth it was forced out again in the mountains by the pressure due to gravitation of the overlying rocks."

Pythagoras (born about 580 B.C.) also left no writings. The Pythagorean philosophy as detailed long after the death of the founder by Ovid in his "Metamorphoses" (about 1 B.C.) details the evaporation-condensation theory, but does not mention springs. After mentioning the four elements Ovid writes:

> All things are mixed of these, which all contain,
> And into these are all resolved again:
> Earth rarefies to dew; expanded more
> The subtle dew in air begins to soar.
> . . . .
> And dew condensing, does her form forego,
> And sinks a heavy lump of Earth below.
> . . . .
> Thus are their figures never at a stand,
> But changed by Nature's innovating hand;
> All things are altered, nothing is destroyed,
> The shifted scene for some new show employed.

Plato must be passed over as merely putting into the mouth of Socrates, a few hours before his death by the hemlock (399 B.C.), a theory of the Earth and its waters which Socrates says is easier to describe than defend. It deals largely with Tartarus and is similar to the Mosaic Abyss and the four rivers flowing out from Eden. Although no mention is made of springs, the myth is sometimes cited as classing Plato with the ocean-fed theorists.

The great philosopher Aristotle (384-322 B.C.), who wrote the first book to bear the name Meteorology, was the first writer to attempt a complete scientific account of the origin of springs and rivers. He held that both come from the condensation of moisture--the one from above, the other from within the Earth. Let us now have Aristotle's own words under the headings "Sources of rains" and "Sources of rivers," bearing in mind that, although he wrote about the formation of springs, he had no such heading. First, as to rivers:

> "[The region] which immediately surrounds the Earth [is] common to water and air, and the processes attending the formation of water above take place in it. The efficient and chief and first cause [of the formation of water] is the circle in which the Sun moves . . . the Earth remains but the moisture surrounding it is made to evaporate by the Sun's rays and the other heat from above, and rises. But when the heat which raises it leaves it, in part dispersing to the higher region, in part quenched through rising so far into the upper air, then the vapor cools because its heat is gone and because the place is cold, and condenses again and turns from air into water. And after the water has formed it falls down again to Earth. . . . So the moisture is always raised by the heat and descends to the Earth when it gets cold again. . . . When water falls in small drops it is called a drizzle; when the drops are larger it is rain." (Book I, Chap. IX, 346 b.)

Under "Origin of rivers" Aristotle first cites the subterranean-reservoir theory held by some others:

> "It is thought [by some] that the water is raised by the Sun and descends in rain and gathers below the Earth and so flows from a great reservoir, all the rivers from one, or each from a different one. No water at all is generated, but the volume of the rivers consists of the water that is gathered into such reservoirs in winter. Hence rivers are always fuller in winter than in summer, and some are perennial, others not. . ."

He disposes of this in a sentence:

> "But if any one will picture to himself a reservoir adequate to the water that is continuously flowing by day and consider the amount of water, it is obvious that a receptacle that is to contain all the water that flows in a year would be larger than the Earth, or at any rate not much smaller."

Next comes Aristotle's back-handed remark to the effect that water is condensed from within as well as outside the Earth, but with no mention of its being stored in underground reservoirs:

> "Though it is evident that many reservoirs of this kind do exist in many parts of the Earth, yet it is unreasonable for any one to refuse to admit that air becomes water in the Earth for the same reason as it does above it. If the cold causes the vaporous air to condense into water above the Earth we must suppose the cold air in the Earth to produce this same effect, and recognize that there not only exists in it and flows out of it actually formed water, but that water is continually forming in it too."

In what follows Aristotle again denies that rivers flow from subterranean reservoirs, tells in effect how springs head underground and feed rivers, particularly in the mountains, and again denies that rivers "originate in definite reservoirs":

> "Again, even in the case of the water that is not being formed from day to day but exists as such, we must not suppose as some do that rivers have their source in definite subterranean lakes. On the contrary, just as above the Earth small drops form and these others, till finally the water descends in a body as rain, so too must we suppose that in the Earth the water at first trickles together little by little, and that the sources of the rivers drip, as it were, out of the Earth and then unite. This is proved by facts. When men construct an aqueduct they collect the water in pipes and trenches, as if the Earth in the higher ground were sweating the water out. Hence, too, the headwaters of rivers are found to flow from mountains, and from the greatest mountains there flow the most numerous and greatest rivers. Again, most springs are in the neighborhood of mountains and high ground, whereas if we except rivers, water rarely appears in the plains. For mountains and high ground, suspended over the country like a saturated sponge, make the water ooze out and trickle together in minute quantities in many places. . . . . It is clear then that we must not suppose rivers to originate in definite reservoirs." (Book I, Chap. XIII, 349 b.)

In his exposition of the Epicurean Philosophy called "De Natura Rerum" the poet Lucretius (about 99-55 B.C.) gives a clearer exposition of the forces of Nature engaged in the pluvial cycle than did Aristotle in his "Meteorology." A notable feature of Lucretius' poem is the passage in which he raises and answers the question why does the ocean which receives all the rivers, not overflow. The answer, from Creech's rhymed translation of the seventeenth century, is:

> The Sun drinks some, to quench his natural heat;
> And some the winds brush off. . . .

Some passes through the Earth, diffused all o'er,
And leaves its salt behind in every pore;
For all returns thro narrow channels freed
And Joyns where e're fountain shows her head;
And thence fine streams in fair Meadows play.

In his more specific account of the origin and circulation of waters Lucretius first describes the formation of clouds and rain. Clouds begin with the combination of "many particles of rougher kind." These are driven together by winds, added to from below by rising mists and compressed from above by "emanations from the starry ether" until "a wet of clouds" is formed "beneath the blue." These and other "first beginnings" result in "storm and darkness hanging from above."

On rain or the discharge of "seeds of water" the poet says, quoting now from Jackson's rhythmic prose translation:

> ". . . . When the winds bear clouds, hanging like woolen fleeces, over the great sea, they often gather much sea-water. In a like way moisture is taken up into the clouds from the rivers. . . the winds' force thrusts them [clouds] in collision . . . . and makes showers flow out . . . . [and sometimes there are heavy rains]."

Toward the end of this section Lucretius says that sea-water oozes into adjacent porous soil, is sweetened and oozes back again, "converging to the river-head." After this it pours once more "o'er the lands." He enlarges upon an idea previously expressed, implying an ocean-fed theory, kept secondary to the pluvial origin of springs.

The first engineer to describe the origin of springs was the Roman, Vitruvius. This he did in the eighth of his "Ten books of architecture" written about 15 B.C. In essence he was in accord but in detail he was clearer and more specific than either Aristotle or Lucretius in their pluvial theories. Besides he brought in the idea of Earth's strata affecting springs.

Vitruvius was treating primarily of sources and quality of water-supplies. Taking out and arranging in logical order what he wrote on evaporation and condensation, precipitation and springs, we have the following:

> [Evaporation and condensation] That vapor and mists and humidity come from the Earth, seems due to the reason that it contains burning heat, mighty currents of air, and a great quantity of water. So soon as the Earth, which has cooled off during the night, is struck by the rays of the Sun, and the winds begin to blow while it is yet quite dark, mists begin to rise upward from damp places. . . .
>
> [Precipitation] Whenever the winds carry the vapor which rolls in masses from springs, rivers, and marshes and the sea it is brought together by the heat of the Sun, drawn off, and carried upward in the form of clouds: Then the clouds are supported by the current of air until they come to the mountains where they are broken up from the shock of collision and the gales, turn into water on account of their fullness and weight and in that form are dispersed upon the Earth (as rain). . . .
>
> [Springs] The valleys among the mountains receive the rain most abundantly, and on account of the thick woods, the snow is kept in them longer by the shade of trees and mountains. Afterwards, in melting, it filters through the fissures in the ground and thus reaches the very foot of the mountains, from which gushing springs come belching out.
>
> But in flat countries, on the contrary, a good supply cannot be had. For however great it is it cannot be wholesome, because as there is no shade in the way, the intense force of the Sun draws up and carries off the moisture from the flat plains with its heat, and if any water shows itself there, the lightest and the purest and the delicately wholesome part is summoned away by the air, and dispersed to the skies, while the heaviest and the hard and unpleasant parts are left in springs that are in flat places.

Quite incidentally Vitruvius mentions deep-seated waters and Earth strata. Nowhere does he show a conception of the existence and functions of permeable and impermeable inclined strata, in the origin and movement of underground waters.

Hot springs, Vitruvius says, are brought to the surface by heat and entrained air. He adds:

> "When such springs are not opened but confined by rocks, the force of the air in them drives them up through the narrow fissures to the summits of the hills [italics mine]. as long [as such springs] are confined to narrow channels, the currents of air in the water run up in bubbles to the top, but as soon as they are given wider outlets, they lose their air on account of the rarity peculiar to water, and so settle down and resume their proper level."

Coming near the end of the classical period and the beginning of extensive reviews of theories as to the origin of springs, we find the third of Seneca's seven books on natural history ("Questions Naturalis") (63 or 64 A.D.) devoted to "Forms of water" including the circulation of water on and in the Earth. The review scarcely mentions the pluvial theory. Seneca's belief was that condensed internal vapors fed springs. Rainfall, he declared, cannot possibly be the source of springs because it penetrates only a few feet into the Earth whereas springs are fed from deep down. As to the former Seneca declared: "As a diligent digger among my vines I can affirm my observation that no rain is ever so heavy as to wet the ground to a depth of more than ten feet." This assertion seems to have been undisputed for centuries with curtailments by some to two feet.

After Seneca there was an almost unbroken silence on the origin of springs until the sixteenth century. When the voices again became active, it was for the most part only to revive one or other of the old theories, often with interesting variations in detail and sometimes with fantastic embellishment. Now and then there were refreshing contributions of new physical data from visual inspection of rivers, brooks, and springs, and from crude rain-gages.

One of the most fantastic embellishments was embodied by the astronomer, Kepler, in his "Harmonices Mundi" (1619). According to Keilhack, the astronomer said "that the Earth forever drinks in water from the sea, like a great beast, digests and assimilates it in its body" adding that "ground-water and springs are the end-products of the Earth's metabolism."

A century later Athanasius Kircher, in his "Mundus Subterraneous" (1717), advanced a theory, illustrated by a diagram, in which he assumed "Hydrophylacia" and "Pyrophylacia" or water and fire caverns (prisons) in the crust of the Earth, fed respectively by the sea and a great fiery mass at the center of the Earth. The first of these, with the aid of heat, causes springs; the second gives rise to volcanoes. Keilhack says that Kircher's general idea as to volcanic action is in line with "the most modern of all theories of volcanic action, that of Stubel."

Mariotte in his book of 1686 restated with improvements the pluvial theory of the origin of springs, refuting the ocean-fed theories and the claims that rainfall penetrates only a few feet into the ground. His great contribution to hydrology was his rainfall-measurements, the application of the results to the computation of the relation between rainfall and runoff, and his conclusions that rainfall is sufficient to feed springs and rivers.

Unlike Kepler, the earlier astronomer, Halley, of comet and other fame, added materially to the knowledge of water-circulation. In 1693 he reported to the Royal Society results of studies he had some time earlier been instructed to make on how much water is evaporated from the sea in a day and Nature's method of returning that vapor to the sea. His conclusion, supporting the pluvial origin of springs, was not so remarkable as the fact that he made an extended study of the subject. Among his supporting data were observations of vapors and their condensation while he was on an astronomical mission to St. Helena. One of his general conclusions was that winds carry vapors to mountain tops where they precipitate, "gleeting down by the crannies of the stone" and finally breaking out by the "sides of the hills" as "single springs." More important was a conclusion on what we would now call the runoff of streams. He wrote: "And it may almost pass for a rule that the magnitude of a river or the quantity of water it evacuates is proportional to the length and the height of the ridges from which its fountains arise." Although lacking several factors recognized later, this showed progress in knowledge.

In 1660 John Ray delivered two series of sermons which contained germs of two books which he published nearly at the close of the century. Ray describes a brook flowing close by his dwelling. This he had ascended to its source, noting that it was fed by numerous rivulets along the way and by a spring at the top which in turn must be supplied with water from adjacent ground. All this water evidently came from rain. Applying these observations to several large European rivers whose courses he had inspected, he wrote that they "did not seem to him to bear any greater proportion to the rivers and rivulets they receive and the immense tracts of land that fed them than my small brook doth to its small rills and compass of ground." This is in line with the rule of Halley already given.

Bare mention can be made in passing to the French popular scientist, Pluche, who in his

"Spectacle de la Nature" (1732) took the youth he was instructing to the outcrops of strata in the city of Laon on the upper part of the mountain of the same name, and to springs from lower outcroppings of the same strata. In this way Pluche visualized the pluvial origin of springs.

At the close of the eighteenth century Erasmus Darwin, grandfather of Charles, and partial anticipator of the latter s "Origin of species," made practical use of his knowledge of exposed inclined strata to rejuvenate a bad well by sinking one within it to a stratum that he knew outcropped at a higher level. He also described the origin of springs in his poem the "Botanic Garden" and in his prose work "Phytologia."

Into the nineteenth and twentieth centuries, with their development of geological and hydrological knowledge and scientific data, and their use to provide water for potable and industrial purposes, it is not the intent of this paper to enter.

[Note--The preceding paper has been prepared from original sources or at least from the earliest available transcripts of such sources. Views of modern authors regarding the precise meaning of some of the earliest writers do not always agree. The reader may find it interesting to compare the preceding paper with two other recent notable accounts of the historical development of the theories on the origin of ground-water: (1) The history and development of ground-water hydrology, by O. E. Meinzer, J. Wash. Acad. Sci., v. 24, No. 1, Jan. 15, 1934; and (2) The origin of springs and rivers--an historical review, by F. D. Adams, Fennia 50, No. 1, Helsingfors, Finland, 1928 (abstract in Geol. Soc. Amer. Bull. 39, pp. 149-150, 1928, and note on Rainfall and runoff in Science, v. 67, pp. 500-501, 1928.]

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Voorheesville, New York (REH)

SEVERAL METHODS OF STUDYING FLUCTUATIONS OF GROUND-WATER LEVELS

Leland K. Wenzel

(Published with the approval of the Director, U. S. Geological Survey)

As a result of increased interest in ground-water conditions in recent years, records of water-levels in wells are now being collected in many places in the United States for the primary purpose of determining the relation of precipitation and other natural factors to fluctuations in water-level. In the past, records of ground-water levels have been collected chiefly in connection with intensive investigations in areas where the water-levels were affected by artificial withdrawals and it has not been generally possible to correlate water-level fluctuations closely with natural factors. It now appears probable that certain methods of studying water-level fluctuations may be utilized advantageously in areas unaffected by heavy artificial withdrawals, but these methods generally do not yield satisfactory results in areas where there is considerable pumping or artesian flow. Three such methods are presented in this paper. The methods have not been given intensive study and their practical use is therefore not yet fully known. It is hoped that their application will be further investigated. Illustrations of the methods have been taken from records of ground-water levels in the Platte River Valley, Nebraska, collected by the United States Geological Survey in cooperation with the Conservation and Survey Division of the University of Nebraska.

Seasonal water-level method

One of the most apparent cycles observed in water-level fluctuations is the seasonal cycle. The use of water by plants in the summer causes the water-level in many areas to decline, and recharge from precipitation and stream-flow in the intervening months generally causes a rise. Hence, the ground-water level in many places rises in the fall, winter, and spring, and declines in the summer even when the major trend--usually the result of several successive years of deficient or greater than normal precipitation--is downward or upward. This seasonal cycle or fluctuation often obscures the major trend of the water-level and also makes difficult the correlation of precipitation and other natural factors with water-level fluctuations.

The effects of seasonal cycles may be partly corrected for by determining the average seasonal fluctuation and eliminating it from the water-level curve. The resultant curve so determined will show fluctuations that are greater or less than average and may consequently reveal the effects of precipitation in greater detail than the original water-level curve. This method may be called a seasonal water-level method and the water-level curve obtained by correcting for average seasonal fluctuations may be called a departure from average water-level curve.

The average annual fluctuation in water-level is first obtained by determining the average stage of the water-level on selected days of the year for the period of record. For example, the average stage on January 1 may be obtained by adding together all the water-levels on this date for the period of record and dividing this figure by the number of water-levels used in the computation. The average stages on February 1, March 1, etc., are obtained in the same manner. The difference in stage between the actual water-level on the first day of each month and the average level on that date is then ascertained for the period of record. A curve showing departures from average water-levels is then plotted from the differences between the average and actual water-levels.

The curve showing departures from average water-levels, by the nature of its construction, is likely to differ from the curve showing actual fluctuations of water-level. Whenever the water-level declines an amount greater than average for that month, the curve showing departures from average water-level declines, and whenever the water-level rises an amount greater than average for that month, the departure curve also rises. In these instances the two curves show similar trends. When, however, the water-level declines an amount less than average, the departure-curve rises, and when the water-level rises an amount less than average, the departure-curve declines. Moreover, when the water-level rises or declines an amount equal to the average for that month, the departure-curve is horizontal.

The departure-curve indicates the relative position of the water-level at any time. The zero-line along which the curve is plotted represents at every point the average level on that day of the year; hence, the distance of the curve above or below the zero-line denotes the distance that the water-level is above or below its average position on that date.

An illustration of the method has been prepared from the fluctuations of water-level in well Dawson-25 in the Platte River Valley, in central Nebraska (Fig. 1). The water-level in this well ranges from 4-1/2 feet to seven feet below the land-surface. The measurements of depth to the water-level have been converted to heights above an arbitrary datum, the datum selected being 100 feet below the water-level in the well on January 1, 1935.

An inspection of the graphs in Figure 1 shows that there is a fair correlation between the precipitation at Lexington and the fluctuations of water-level in the well. The precipitation was above normal in certain months in 1931, 1932, 1933, and 1935, and the resultant rises in water-level in the well are shown by the hydrograph. Similarly, the effect of the drought in 1934 is shown by the large decline of water-level in that year. However, the effects of precipitation on the water-level in the well are in some instances shown more clearly by the curve showing departures from average water-levels. For example, the precipitation in June and July 1932 was about 4.4 inches above normal but there was no net change of water-level in the well. The curve showing departures from average water-levels rose, however, on August 1 to the highest stage of the 5-year period, a level of over one foot above the average stage on that date, thus indicating that the water-level in the well was maintained by the precipitation during a period when a relatively large decline normally occurred. The departure-curve also shows the effects of the deficient precipitation in the period from August 1932 to March 1933. Although the water-level in the well rose from October 1 to March 1, the departure-curve declined, because the rise

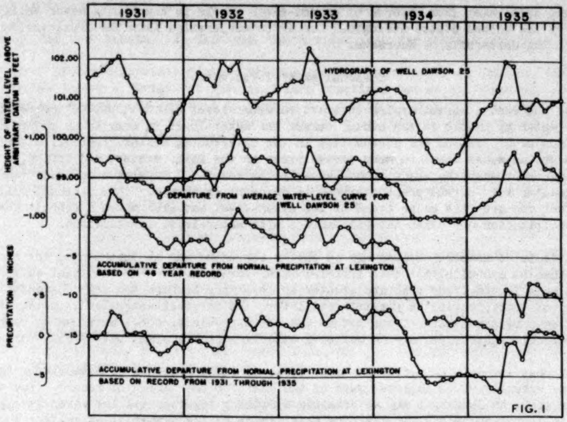

FIG. 1

GRAPHS SHOWING COMPARISON BETWEEN FLUCTUATIONS OF WATER LEVEL IN WELL DAWSON 25 AND THE PRECIPITATION RECORDED AT THE STATION OF THE U. S. WEATHER BUREAU AT LEXINGTON, NEBR.

in water-level was less than the average rise in these months.

Method of showing long-time water-level trends

The water-levels in most wells rise and decline many times each year, and as a result long-time trends are often obscured. Seasonal fluctuations, as previously mentioned, especially tend to obscure water-level trends. It is often helpful to utilize some method that is primarily designed for showing water-level trends when studies of this kind are made.

One method of showing water-level trends consists of the use of what is sometimed called "moving averages." Records of water-levels extending for relatively long periods are essential

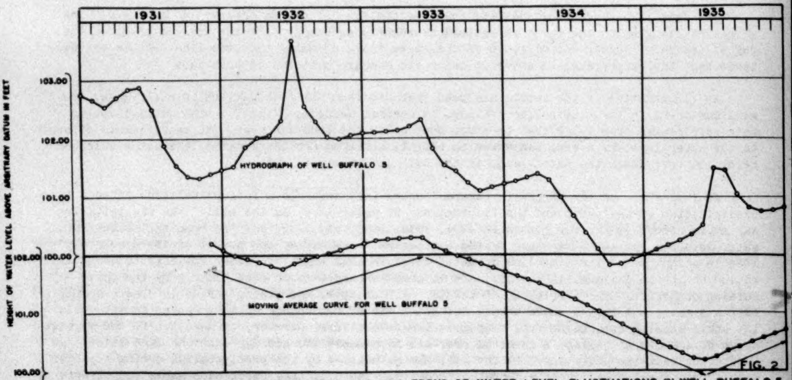

FIG. 2

HYDROGRAPH AND MOVING AVERAGE CURVE SHOWING TREND OF WATER-LEVEL FLUCTUATIONS IN WELL BUFFALO 5 NEAR KEARNEY, NEBRASKA for the use of this method, and it is also necessary that the water-levels be available at definite and equal time-intervals. When this method is applied to the study of water-levels, it is necessary to obtain records of the water-level on certain dates of each year, such as the first day of each month, or the first day of every third month. The sum of successive levels for a selected period is first determined and the average level is then obtained by dividing the sum by the number of dates considered.

After the average water-level for a selected period at the start of the record has been obtained the next successive water-level is added to the sum and the first water-level is deleted. A new average is then obtained for the period. The new average obviously relates to one time-unit later than the first average. The addition of later water-levels, the deletion of earlier water-levels, and the computing of new averages is continued throughout the period of record.

An illustration of this method has been prepared from the fluctuations of water-level in well Buffalo-5 in the Platte River Valley, Nebraska (Fig. 2). In this instance monthly intervals were selected and the water-level on the first day of each month was determined for the period from January 1, 1931, to January 1, 1936. An interval of one year was selected for the moving period. Hence, each average water-level obtained represents the average water-level, expressed in feet above an arbitrary datum, for one year.

Each average value includes one year's seasonal fluctuation, irrespective of the beginning and ending of the period considered. Thus, the moving average curve will not necessarily rise when the water-level rises or decline when the water-level declines, but will indicate distinctly the position of the water-level with respect to its position one year previous. If the curve shows a rise, this indicates that the water-level at the end of the period considered is higher than it was a year previous, and conversely, if the curve shows a decline, this indicates that the water-level on the last date considered is lower than it was the previous year. If the water-level on both dates is the same, the curve will be horizontal.

There are four distinct water-level trends shown by the moving-average curve in Figure 2 that are indicated by arrows. For the six-month period from December 1, 1931, to June 1, 1932, the trend was downward. For the next 12 months the water-level trend was upward, but for the following 24 months the trend was again downward. Beginning July 1, 1935, the water-level trend turned upward and this trend was still in progress on January 1, 1936.

Method of estimating amount of precipitation required to increase ground-water storage

The amount and frequency of recharge to the zone of saturation is largely dependent on the moisture-conditions in the material above the water-table. Where the water-table is shallow the capillary fringe may extend to or near the land surface and most plants may draw water for their growth from the zone of saturation. As a result, the moisture in the soil generally is not greatly depleted and the deficit of soil-moisture that does exist usually is satisfied by comparatively light precipitation, thus frequently allowing water to percolate downward to recharge the zone of saturation. Where the water-table lies deeper, the roots of most plants may obtain water from the soil and the moisture held in it is generally less than in areas of shallow water-table. Thus, in such areas the deficit of soil-moisture is likely to be relatively large at most times, and recharge to the zone of saturation usually occurs only after moisture has accumulated in the soil from a series of rains. In some places, especially in arid or semiarid regions, the precipitation is not usually sufficient to satisfy the deficit of soil-moisture in the growing season and recharge may take place only near the end of the dormant season after considerable moisture has been added to the soil.

Theoretically, if a certain deficit of moisture exists in the soil at the end of a growing season, and if this amount is ascertained, then there can be estimated the approximate amount of precipitation required to cause a net increase in ground-water storage in the subsequent dormant season. In general, the size of the deficit of soil-moisture at the end of a growing season depends on the amount of precipitation in that season; that is, the deficit will be small if the precipitation during the growing season is large and the deficit will be large if the precipitation is small. Hence, more precipitation is required to produce recharge after a dry growing season than after a wet growing season. This general rule does not, however, take account of the distribution of the precipitation in the growing season, which is also a factor in the seasonal transpiration.

The part of the growing season in some areas, such as in Nebraska, when recharge is least likely to occur in areas where the water-table lies relatively deep, extends from about July 1 to about November 1. Although plants draw water from the root-zone in April, May, and June,

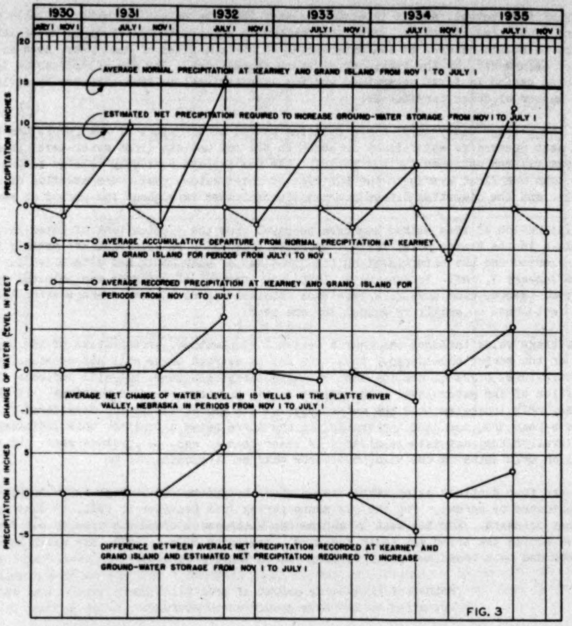

FIG. 3

GRAPHS ILLUSTRATING METHOD OF ESTIMATING AMOUNT OF PRECIPITATION REQUIRED TO INCREASE GROUND-WATER STORAGE, PLATTE RIVER VALLEY, NEBRASKA

recharge often occurs in these months because of the relatively small deficit of soil-moisture that may exist at the beginning of the growing season. Hence, the deficit of soil-moisture that exists in the root-zone at the end of a growing season is more likely to be related to the amount of precipitation in the period after a deficit has been definitely created rather than to the precipitation in the entire growing season.

An approximate figure for the deficit of soil-moisture at the end of the growing season may be determined by ascertaining the departure from normal precipitation during the period July 1 to November 1. To this figure may be added the total precipitation in the subsequent period from November 1 to July 1, and the resultant sum may be compared with the net change in ground-water storage from November 1 to July 1. The resultant precipitation--that is, the net precipitation--required to cause an increase in ground-water storage in the period may be approximated by a comparison of the amounts of net precipitation in years when the water-level rose with the amounts of net precipitation in other years when the water-level declined.

An illustration of the method has been prepared from the records of precipitation at Grand Island and Kearney, Nebraska, and the records of water-level in 15 wells in the Platte River Valley (Fig. 3). The departure from the average precipitation at Grand Island and Kearney from July 1 to November 1 for the six years of record, 1930 to 1935, is shown in the Figure by dashed lines and the actual precipitation in the subsequent 8-month periods is indicated by full lines. The precipitation from July 1 to November 1 in all six years has been below normal, ranging from 1.21 inches in 1931 to 6.08 inches in 1934.

A comparison between the graphs in Figure 3 showing net precipitation and those showing net change in water-level indicates that the water-level rose in years when the net precipitation was more than about 9.5 inches and declined in years when the precipitation was less than this figure. Thus, it may be assumed that 9.5 inches of precipitation will be required from November 1 to July 1 to increase the ground-water storage in this period, provided the precipitation in the 4-month period prior to November is normal. Presumably, more or less than 9.5 inches of precipitation will be required if the precipitation from July 1 to November 1 is below or above normal.

An appreciable decline in water-level usually occurs from July 1 to November 1; thus an equivalent net rise must be registered from November 1 to July 1 in order to maintain the water-level at approximately the same stage throughout a period of years. The amount of net precipitation required to cause this rise in water-level may be approximated by first determining the average decline from July 1 to November 1, and then ascertaining the net precipitation in years when the water-level rose this or greater amounts. The average net decline in the 15 wells in the Platte River Valley from July 1 to November 1 is 0.52 foot. It is estimated from Figure 3 that 11 to 12 inches of net precipitation will be required to produce this amount of net recharge. These figures are only very rough approximations inasmuch as the decline from July to November will be larger when the water-level is high and smaller when the stage of the water-level is low. Moreover, large differences in the amount of recharge may be produced by variations in the intensity and distribution of the precipitation.

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THE EFFECT OF DISTANT EARTHQUAKES ON THE WATER-LEVEL IN WELLS

F. B. Blanchard and Perry Byerly

The writers have described elsewhere (Bull. Seis. Soc. Amer., v. 25, pp. 313-321, 1935) the results of the experiment of installing a water-stage recorder with greatly extended time-scale on a well at Lodi, California. This well was known to be susceptible to distant earthquakes. During the experiment it recorded the individual pulsations caused by the passage of seismic waves. Some hydrological aspects of the work will be briefly discussed here.

It is shown in the previous paper that the phenomenon may be analytically explained as due to alternate dilatation and contraction of a confined aquifer resulting from the phase-difference of the opposite sides during the passage of longitudinal waves. This is an extension of H. T. Stearns' (Bull. Seis. Soc. Amer., v. 18, pp. 9-15, 1928) conclusion that the effect is due to compression of confined aquifers in a deep well, similar to that caused by passing railroad trains. According to this explanation, the transverse or shear waves, being equi-voluminal, would not directly affect the water-level in the well, though they may do so indirectly through transformation to longitudinal waves at the ground-surface. The well-water motion magnifies the amplitude of Earth-motion by a factor called the phreatic magnification, which is a function of the dimensions of the well and the aquifer it taps. In the former paper the following expression was derived for this quantity:

$$M = H/E = 2\pi/\lambda[(A/V) + (\rho g/b)] \qquad (1)$$

where H = amplitude of the float-motion (in most cases nearly identical with the well-water motion); E = amplitude of the longitudinal wave earth-motion; λ = wave-length of the incident longitudinal earth-motion; A = area of cross-section of the well; V = volume of the underground water-body; ρ = density of the water; g = gravitational acceleration; and b = bulk-modulus of water.

Solving for V gives

$$V = \lambda bAM/(2\pi b - \rho g\lambda M) \qquad (2)$$

Hence if it were possible to determine λ and M by some independent means, the value of V would become known. This means might be supplied by a pendulum-seismograph, from the records of which the ground-motion, E, could be computed and used for obtaining M. The wave-length, λ, could be computed by the relation $\lambda = vt$, v being the longitudinal wave-velocity for the medium around well, and t the period of the earth-waves. Due to the lack of a seismograph, it was not possible to obtain the value of M at Lodi; hence no determination of V for the well could be made.

The assumptions underlying the derivation of the formula are open to a number of hydrologic objections, such as (1) that there is a constant mass of water in the well and aquifer, and (2) that viscous losses due to the flow of water into and out of the well are negligible. From the seismological point of view, the assumption of simple harmonic earth-motion is also objectionable. The importance of these factors can only be determined by further work which is necessary before the method may be considered applicable.

A disadvantage of the formula should be pointed out. For very large values of V/A, the phreatic magnification becomes sensibly independent of the volume of the aquifer, the response of the well is no longer a good index of its volume, and ultimately the formula reduces to

$$M = H/E = 2\pi b/\rho g\lambda \tag{3}$$

which is independent of the volume. The result of this is that, for example, with a 6-inch well, penetrating an aquifer containing 30 acre-feet of water, an accuracy in M within one per cent would be required to evaluate V within ten per cent. Thus the determination of very large volumes is impractical. On the other hand, an 18-inch well would permit the determination of a volume of nearly 300 acre-feet with the same accuracy. An accuracy within one per cent in the determination of M would be hard to attain. Hence it may be doubted whether the method will find a practical use, and it is here presented primarily for its theoretical interest.

A rough verification of formula (3) was made in the following way. For the Lower California Earthquake of December 30, 1934, recorded at the well, the first well-water motion in the P-phase was computed by the formula, using for the earth-motion at Lodi the first ground-motion of the first preliminary waves at Berkeley as computed from the records of the Bosch-Omori and Wiechert seismographs. This computed amplitude by formula was 0.035 cm as compared with the observed amplitude recorded by the instrument of 0.040 cm. This agreement tends to substantiate the formula, although it is recognized that the neglect of transients in both cases (earth-motion at Berkeley and water-motion at Lodi) is questionable.

For a well equipped with a pressure recording-device, such as the artesian wells reported by Leggette and Taylor (Bull. Seis. Soc. Amer., v. 25, pp. 169-175, 1935), the value of A/V is practically zero. Hence we have $M = H/E = 2\pi b/\rho g\lambda$. Since the recording is in pressure-units, $H/E = p/\rho gE = 2\pi b/\rho g\lambda$ and $p = (2\pi b/\lambda)E$ where p = amplitude of pressure-change.

During large earthquakes it is well known that underground waters are frequently forced up in the form of earthquake-fountains. These flow for a short time. In the earthquake of 1906, sand brought up from such fountains near Salinas came from a depth of 80 feet. It is conceivable that the effects of earthquake-waves in the vicinity of the epicenter of a large earthquake might cause some spurting of water in this fashion. However, the continued flow frequently observed is probably due to an actual displacement of part of the aquifer.

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NATURAL STREAM CHANNEL-STORAGE

Robert E. Horton

It is assumed that the reader has some familiarity with the author's infiltration-theory of runoff$^{(1)}$ and also with Sherman's unit-graph method of calculating runoff$^{(2)}$. [References: (1) Robert E. Horton, The role of infiltration in the hydrologic cycle, Trans. Amer. Geophys. Union, 14th annual meeting, pp. 446-460, 1933, and Surface-runoff phenomena: Part I--Analysis of the hydrograph, Pub. 101, Horton Hydrologic Laboratory, Edwards Bros., Inc., Ann Arbor, Mich., 1935; (2) Water-Supply Paper 772, U. S. Geol. Surv., 1936.]

Figure 1 is an example of a channel-outflow graph for Wabash River above Logansport, Indiana, August 1929, from Water-Supply Paper 772, United States Geological Survey, 1936 (the original graph as plotted from daily average discharges has been corrected to allow for the fact that the peak is higher than the crest-day average). In a previous paper (op. cit., Pub. 101) the author showed: (a) Direct surface-runoff ends soon after rainfall ends--sometimes a little earlier; the time at which the direct surface-runoff ends is usually at or near the point of inflection a (Fig. 1) on the hydrograph. (b) After direct surface-runoff ends on a drainage-basin without surface-storage in reservoirs, lakes, swamps, and marshes, the entire flow at a given point, gaging-station, or outlet, is derived either from ground-water flow or channel-storage until the effects of subsequent rainfall begin to appear in the stream.

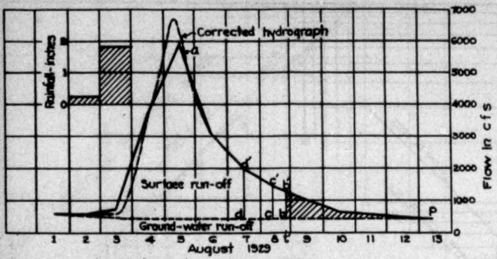


FIG. 1- WABASH RIVER ABOVE LOGANSPORT, IND.
STREAM-RISE OF AUG. 2-12, 1929

It is generally possible by different methods to draw a line separating the ground-water or base-flow from the surface-runoff, such as the dotted line of Figure 1.

It can be shown analytically that, subject to one exceptional case, if there is a constant or nearly constant rate of ground-water flow entering a stream, the channel-storage will drain out in a finite time, ending at a point p (Fig. 1), where there is, as a rule, a more or less abrupt flattening of the slope of the recession-side of the graph.

It is easy to see that at any time t', measured backward from the end of the channel-storage outflow, the shaded area on Figure 1 represents the total volume of channel-storage which remained in the stream-channels comprising the drainage-net of the stream-system at the time t'. Also the ordinate bb' represents the rate of channel-storage outflow at a time when the total volume of channel-storage is as represented by the shaded area. If, now, the area of the graph above the base-flow line and between the points p and a is determined for each of a series of ordinates bb', cc', dd', etc., these data when plotted will show the law of relationship between the rate of channel-storage outflow and the total volume of channel-storage. It can be shown analytically that if the width of the streams is a simple function of the stage, the volume of channel-storage will be a simple power-function of the stage above a suitable reference-plane. If there was no ground-water flow, this would be the plane of zero-discharge at the given gaging-station or outlet.

A stream-channel usually consists of a succession of deeps and shoals, and the fact that a given gaging-station may be located in a deep reach where there is a quiescent pool of water remaining in the channel-bottom at zero-discharge makes no difference since the stage-outflow relation at such a station is determined by the plane of zero-discharge or by the bottom of the channel at a point downstream where there is a rapid forming a low-water control. Ground-water flow can be considered as raising the plane of zero-outflow of channel-storage. Many natural stream-channels have approximately parabolic cross-sections, particularly at control-points. It can easily be shown that if the slope is constant and the width is a simple power-function of the stream-stage, the stage-discharge relation can always be represented by an equation of the form

$$q = K_c h^M \tag{1}$$

where h is the stage above the plane of zero-discharge. Similar equations can be applied, but with different values of the exponent M, where the slope varies as a simple function of the stage. If the stage-discharge relation above the plane of zero-channel storage-outflow is given by the equation

$$q_s = K_c' h^R \tag{2}$$

and the volume of channel-storage is given by the equation

$$S_c = K_s' h^S \tag{3}$$

then the channel storage-outflow rate will be a simple power-function of the volume of remaining channel-storage, expressed by the equation

$$h = \sqrt[R]{q_s/K_c'} = \sqrt[S]{S_c/K_s} \tag{4}$$

from which

$$q_s = K_c'(S_c/K_s)^{(R/S)} = K_c'(S_c/K_s)^{(R-S)} \tag{5}$$

or, letting $M = (R - S)$ and $K_s = (K_c'/K_s^{R/S})$

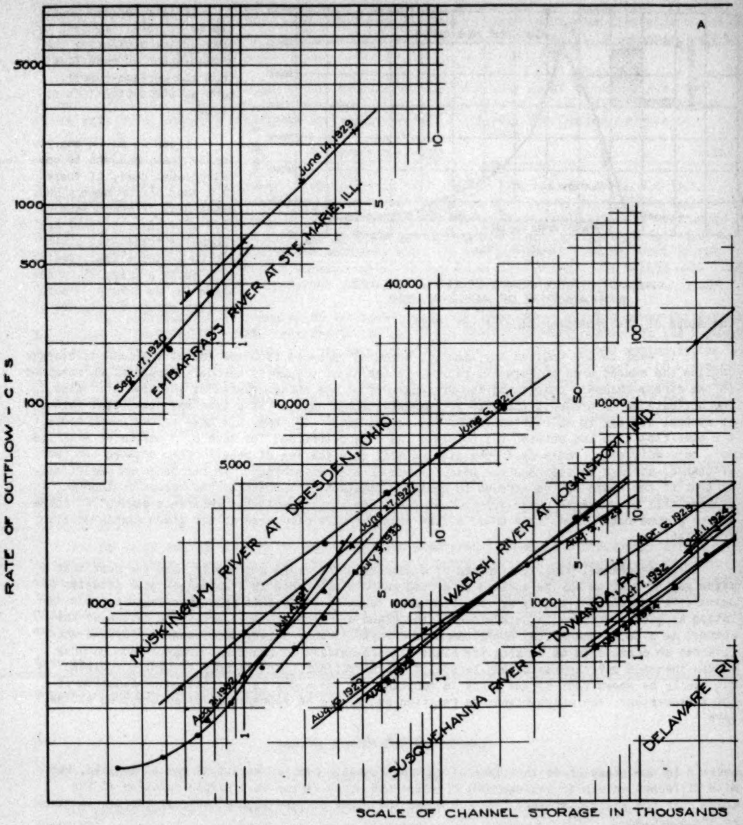
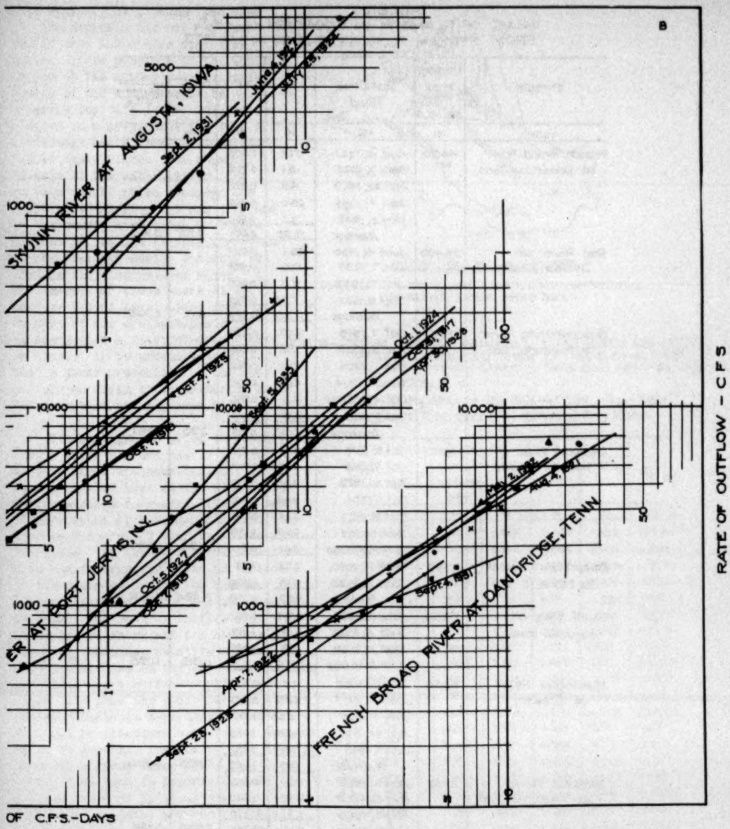


FIG.2-CHANNEL-STORAGE OUTFLOW-VOLUME RELATION LINES

$$q_s = K_s S_c^M \qquad (6)$$

Equation (6) expresses the rate of channel-storage outflow in terms of the volume of remaining channel-storage. If this simple power-function relationship holds true for channel-storage in the stream-system of a given drainage-net, then the values of q_s plotted in terms of the corresponding values of S_c, determined from the recession side of the hydrograph of a stream-rise in the manner described, will plot as straight lines on logarithmic paper and the appurtenant values of K_s and the exponent M can easily be determined.

Water-Supply Paper 772 (Hoyt and others, Studies of relations of rainfall and runoff in the United States, U. S. Geol. Surv., 1936) contains a large number of examples of graphs of stream-rises. These graphs were plotted for use in the study of Sherman's unit-graph method. For this purpose it was deemed sufficient to make a roughly approximate separation of ground-water from



FROM GRAPHS OF STREAM RISES GIVEN IN W.S.P. 772

surface-runoff. Subject to errors from this cause, as subsequently discussed, these graphs furnish an excellent basis for determining if the channel storage-outflow-volume relation is, in fact, a simple power-function in most cases, and also for determining the values and variations of the constants K_s and M in equation (6).

Selecting those graphs in which the recession-side of the graph was reasonably free from surface-runoff from residual rainfall, the volumes of channel-storage were determined and plotted on logarithmic paper and the resulting lines are shown on Figure 2. [Caution is required in plotting such lines not to extend the computation to the left of the point of inflection on the graph, as surface-runoff is then entering the stream and the volume of channel-storage is changing more or less independent of the outflow-rate.] It will be noted that the channel storage-outflow relations are nearly all straight lines. Furthermore, note that they have as a rule nearly the same slope for different graphs on the same stream at the same gaging-station.

TABLE 1
VALUE OF K_s AND M IN EQUATION $q_s = K_s S_c^M$
FROM STREAM-FLOW GRAPHS IN W.S.P. 772

Stream	Drainage Area Sq. Mi.	Date of flood	K_s	M	$\sqrt[M]{K_s}$	$\frac{1}{\sqrt[M]{K_s}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
French Broad River at Dandridge, Tenn.	4,450	Aug. 4, 1921	17.8	0.573		
		April 7, 1922	5.1	0.716		
		Sept. 23, 1923	4.9	0.692		
		Sept. 4, 1931	60.0	0.366		
		May 2, 1932	9.1	0.660		
		Average	19.38	0.601	5.93	0.167
Red River at Denison, Texas.	39,400	June 18, 1930	39.1	0.510		
		Dec. 7, 1930	17.6	0.573		
		Jan. 7, 1932	12.3	0.660		
		Sept. 5, 1932	2.54	0.773		
		Average	17.88	0.629	6.12	0.164
Susquehanna River at Towanda, Pa.	7,770	Oct. 7, 1918	6.02	0.730		
		Apr. 6, 1923	1.92	0.666		
		Oct. 1, 1924	2.91	0.860		
		Nov. 24, 1924	4.63	0.760		
		Oct. 4, 1929	4.61	0.786		
		Oct. 7, 1932	4.19	0.810		
		Average	4.05	0.769	2.93	0.341
Delaware River at Port Jervis, N.Y.	3070	Oct. 31, 1917	4.8	0.793		
		Oct. 7, 1918	0.984	0.946		
		Apr. 30, 1923	4.93	0.773		
		Oct. 1, 1924	5.00	0.800		
		Oct. 5, 1927	4.22	0.786		
		Sept. 5, 1933	0.56	1.185		
		Average	3.41	0.880	2.94	0.340
Embarrass River at Ste. Marie, Ill.	1540	Sept. 17, 1920	0.22	1.13		
		June 14, 1929	0.78	0.965		
		Average	0.50	1.048	0.484	2.065
Skunk River at Augusta, Iowa	4,290	July 25, 1924	0.772	0.963		
		June 4, 1927	0.18	1.152		
		Sept. 2, 1931	1.79	0.893		
		Average	0.914	1.003	0.912	1.098
Muskingum River at Dresden	5,980	June 6, 1927	7.0	0.726		
		June 27, 1927	2.46	0.820		
		July 4, 1927	.048	1.316		
		Aug. 21, 1932	.196	1.098		
		July 3, 1933	.05	1.25		
		Average	1.95	1.042	2.005	0.500
Wabash River at Logansport, Ind.	3830	Aug. 5, 1929	2.61	0.816		
		Aug. 16, 1929	9.10	0.650		
		Aug. 2, 1929	3.71	0.770		
		Average	5.14	0.745	3.390	0.295

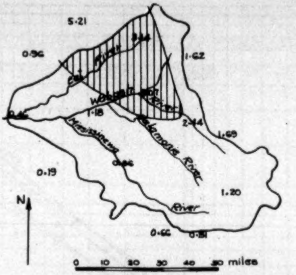
Table 1 shows the values of K_s and M determined from these graphs. It will be noted that the value of the exponent M is relatively constant for different graphs on the same stream. So far as these studies go, the value of the exponent M appears to hover around two values. For many streams M is from 2/3 to 3/4 or not far from (5/3 - 1), the value which it would have if the channel had a constant width within the range of the observations, the slope was constant, the discharge was that corresponding directly to the Manning formula, $q = (1.486/n) W h^{5/3} \sqrt{S}$, and the channel-storage was that corresponding to a channel of uniform width, that is, with the volume of storage increasing directly in proportion to the stage h. For some other streams the exponent M has a value close to but usually a little more than unity.

The values of the coefficient K_s for different graphs taken at the same gaging-station are much more variable than the values of M. It can be shown analytically that the values of both K_s and M are sensitive to the effect of errors in the elimination of ground-water flow. This probably accounts for some of the variation in M and K_s. The major reason for variation in K_s, which represents the rate of outflow from channel-storage when the channel-storage is unity, is that many of the stream-rises used in this analysis did not represent runoff from the entire drainage-basin. It is possible by the application of the author's infiltration-theory of the analysis of the hydrograph (op. cit., Pub. 101) to determine in a given case the part of a drainage-basin from which surface-runoff takes place. For example, in case of the Wabash River, the surface-runoff which produced the graph shown on Figure 1 was confined to the shaded area shown on Figure 3, that is, to the northerly portion of the drainage-basin, entirely excluding the Mississinewa River. A stream-rise or flood where direct surface-runoff takes place from only part of the drainage-basin may be designated a "partial-area rise" or flood. It is undoubtedly true that a large proportion of the runoff graphs given in Water-Supply Paper 772 represent partial-area rises.

The unit-graphs given in Water-Supply Paper 772 are nearly all for relatively large drainage-basins. It is generally true that as the size of the drainage-basin increases, the frequency of occurrence of stream-rises resulting from surface-runoff over the whole basin decreases. If the stream-rise results from runoff from the lower portion only of the drainage-basin, the entire channel-system will not contain channel-storage. The rate of outflow will therefore be increased and the coefficient K_s increases relative to that for a full-area rise on the same stream. The situation where surface-runoff takes place only from the upper portion of the drainage-basin is more complicated and will not be discussed here but it appears that, in general, the coefficient K_s will have its minimum value for a full-area rise. This fact is important since the minimum value of K_s is apparently fairly fixed and definite, and can be applied in computations relating to the most severe floods, which are, in general, full-area floods.

Channel storage-outflow-volume relations were also worked out for a large number of stream-rises on Ralston Creek at Iowa City, Iowa. [The author is indebted to the late Dr. Floyd A. Nagler for data regarding Ralston Creek stream-rises used in the preparation of Figure 4 and Table 2.]

The results are shown on Figure 4 and the values of the coefficient K_s and exponent M for the different rises are shown on Table 2. This drainage-



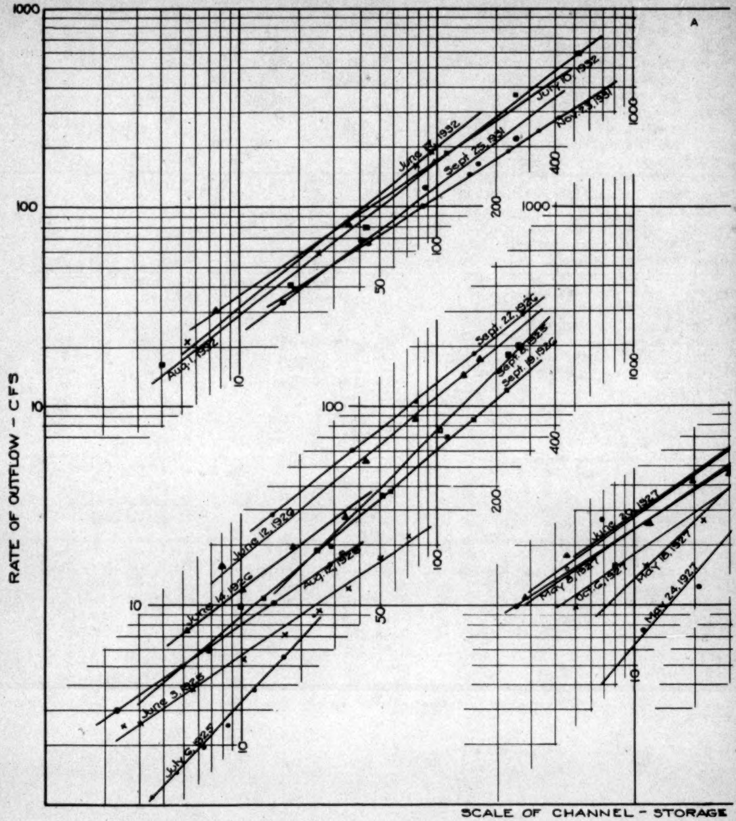
WABASH RIVER BASIN ABOVE LOGANSPORT, IND.
DRAINAGE-AREA 3830 SQ.MI.

FIG 3- TOTAL STORM RAINFALL AND AREA (SHADED) WHICH PRODUCED RISE OF AUG. 5-12, 1929
THE INFILTRATION-CAPACITY WAS 0.30 INCH PER HOUR

TABLE 2

VALUE OF K_s AND M IN EQUATION $q_s = K_s S_c^M$
RALSTON CREEK, IOWA CITY, IOWA

Date	Maximum Rate of Discharge c.f.s.	K_s	M	$\sqrt[M]{K_s}$	$\frac{1}{\sqrt[M]{K_s}}$
(1)	(2)	(3)	(4)	(5)	(6)
June 3, 1925	43	1.205	0.667	1.132	0.883
July 6, 1925	12	0.322	1.050	0.304	3.290
Aug. 12, 1925	21	1.66	0.683	1.414	0.707
Sept. 8, 1925	267	0.78	1.00	0.780	1.283
June 12, 1926	272	2.70	0.81	2.238	0.447
June 14, 1926	45	2.13	0.75	1.763	0.567
Sept. 19, 1926	146	1.33	0.833	1.268	0.787
Sept 22, 1926	380	3.42	0.793	2.65	0.377
May 8, 1927	295	5.02	0.680	2.99	0.334
May 18, 1927	360	1.565	0.946	1.528	0.654
May 23, 1927	95	5.50	0.640	2.98	0.336
May 24, 1927	123	0.434	1.163	0.379	2.640
June 20, 1927	650	5.83	0.689	3.37	0.297
Oct. 2, 1927	385	5.49	0.703	3.31	0.302
Oct. 6, 1927	236	3.70	0.686	2.455	0.407
May 18, 1928	70	3.48	0.759	2.572	0.389
June 24, 1928	220	5.25	0.650	2.94	0.340
July 4, 1928	75	3.87	0.600	2.41	0.415
July 19, 1928	185	4.25	0.651	2.565	0.390
Aug. 23, 1928	353	3.30	0.769	2.500	0.400
June 11, 1929	395	3.38	0.829	2.742	0.365
June 13, 1929	108	2.75	0.883	2.44	0.410
July 1, 1929	200	3.32	0.776	2.535	0.394
Aug. 2, 1929	372	3.12	0.777	2.42	0.413
June 22, 1930	150	5.54	0.670	3.15	0.317
June 14, 1930	735	5.29	0.700	3.21	0.311
July 19, 1931	68	4.55	0.680	2.805	0.357
Sept. 21, 1931	132	5.35	0.658	3.02	0.331
Sept. 25, 1931	250	4.00	0.746	2.815	0.355
Nov. 23, 1931	338	5.79	0.639	3.075	0.325
June 17, 1932	340	4.87	0.800	3.545	0.282
July 10, 1932	270	7.50	0.675	3.90	0.256
Aug. 1, 1932	850	4.85	0.763	3.340	0.299
Average		3.68	0.761	2.441	0.596



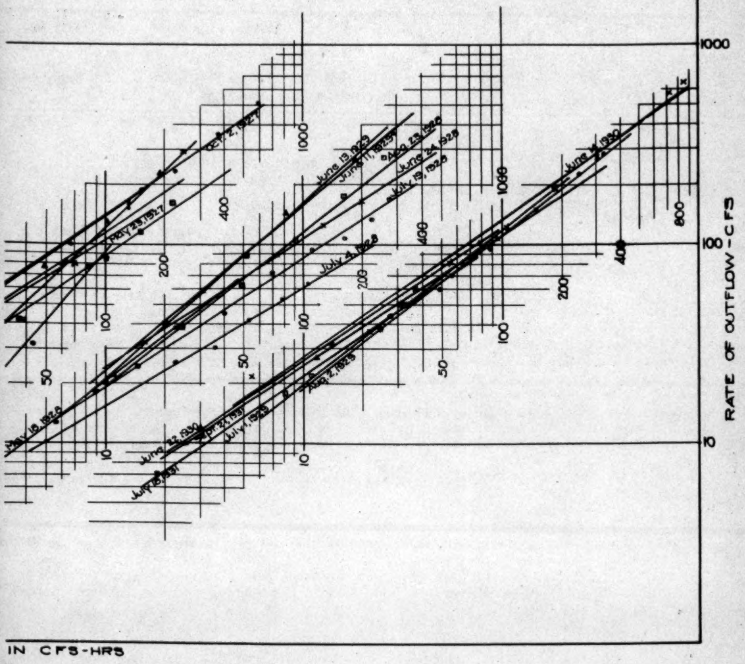
basin comprises only three square miles but, owing to high infiltration-capacity of part of the area during the summer season, it happens that here again many of the rises are partial-area rises, since full-area rises result only from rains having intensities exceeding the highest infiltration-capacity on any part of the drainage-basin. [In preparing the examples of channel storage-outflow-volume relation lines for Ralston Creek, given at p. 39 of Pub. 101, it was assumed that there was no appreciable ground-water flow. Some of the resulting lines show considerable curvature as the stage- and outflow-rates decrease. Later recomputation of these lines, making corrections for ground-water flow, reduces them substantially to straight lines.]

The slopes of the graphs for Ralston Creek (Fig. 4) and the values of the exponent M are of the same order of magnitude and show about the same dispersion as for the larger drainage-basins studied (Fig. 2). In Table 2, as in Table 1, most of the values of M are between 0.60 and 0.80.

Writing equation (6) in the form

$$S_c = \sqrt[M]{q_s/K_s} \tag{7}$$

FIG. 4- CHANNEL STORAGE OUTFLOW-VOLUME RELATION LINES, RALSTON CREEK, IOWA CITY, IOWA



and letting $q_s = 1$, gives

$$S_1 = \sqrt[M]{1/K_s} \tag{8}$$

Equation (8) gives the volume of channel-storage when the channel storage-outflow rate is unity. This quantity will have a maximum value for a full-area rise. Its value for different rises is given in column (7) of Table 1 and column (6) of Table 2.

In the preceding discussion q_s is in cubic feet per second and S_c in c.f.s.-days in Table 1, and in c.f.s.-hours in Table 2. Since one c.f.s.-day equals, very nearly, two acre-feet, channel-storage given in c.f.s.-days can easily be expressed in acre-feet by multiplying these formulae by 2.

Also, since one c.f.s.-day = 0.03719-inch depth on one square mile, channel-storage can easily be expressed in terms of inches depth on the drainage-area. For example, the data for

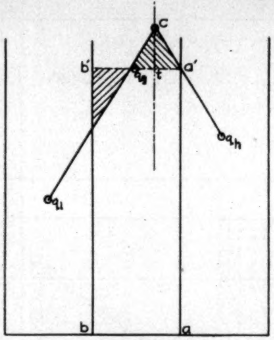


FIG. 5 - CORRECTION OF CREST OF GRAPH PLOTTED FROM DAILY AVERAGE DISCHARGES

Delaware River, given on Figure 2, show that for large floods on that stream the channel-storage may be equivalent to 100,000 acre-feet or 1/2 inch depth on the drainage-basin.

The channel-storage for unit channel-outflow rate as given by equation (8) is apparently a physical characteristic of the storage-capacity of the drainage-net of a given stream-system. Perhaps a better characteristic would be the same quantity reduced to the basis of channel-storage in acre-feet per square mile corresponding to a channel outflow-rate of one c.s.m.

Let S_A be this quantity and A the drainage-area in square miles. Then from equation (8)

$$S_A = 2(S_1/A) \tag{9}$$

Combining equations (6) and (9)

$$S_A = 2A^{(M-1)}/\sqrt[M]{K_s} \tag{10}$$

If applied to full-area rises, this equation should give the maximum channel-storage per square mile of drainage-area corresponding to a channel outflow-rate of one c.s.m.

The data in Tables 1 and 2 afford some indication that K_s and M are inversely related. Owing to the fact that an undetermined portion of the stream-rises included in this study were partial-area rises, no attempt has been made to work out the relation between these quantities or the true values of S_A for full-area rises. The data thus far collected have been presented in the hope that others may pursue similar investigations and publish the results so that these quantities and relations may be further studied and evaluated.

Some studies have been made which indicate that the channel-storage relation once determined for a given stream-system from the recession-side of a graph of a stream-rise can also be applied, approximately at least, throughout the entire stream-rise in case of full-area rises.

Summarized briefly, the above analysis of channel-storage seems to offer the following possibilities of usefulness:

(1) It supplies the missing link in the problem of routing a graph of surface-runoff down a system of stream-channels, approximately at least.
(2) It affords a simple, direct means of determining the volume of channel-storage and the consequent regulating effect of channel-storage on floods.
(3) It appears that the values of the quantities S_1 and S_A are definite physical characteristics of a given drainage-basin.

[Note: The purpose of the present paper being to present facts derived directly from observation, theoretical treatment of the subject has been omitted. Full analytical study of the basis of the equations given has, however, been made and will be published in a subsequent paper.]

Appendix--Correction of crest of runoff-graph plotted from daily discharges

Let q_g = average discharge for crest-day, q_h = average discharge on the higher, and q_ℓ that on the lower, of the two days, one preceding, the other following the crest-day. Then

$$t = 12[(q_g - q_h)/(q_g - q_\ell)]$$

where t is the time of the crest, measured from the dividing line between the crest-day and the higher of the adjacent days. Referring to Figure 5, the crest is on a vertical line through t and is so located that the shaded areas between aa' and bb' and above and below a'b', respectively, are equal. The method is very sensitive and the point can be so located by one or two trials that the shaded areas balance.

A somewhat similar correction is often required at the beginning of an abrupt rise. A smooth curve drawn through the corrected points and through the points corresponding to average discharge for other days will give nearly a correct graph of a rise and permits the inflection-point on the recession-side to be approximately determined and with it the limit of the values of q which may be used in computing storage outflow-rate-volume relations.

Voorheesville, New York

THE CHANNEL-STORAGE METHOD OF DETERMINING EFFLUENT SEEPAGE

O. E. Meinzer, R. C. Cady, R. M. Leggette, and V. C. Fishel
(Published with the approval of the Director, U. S. Geological Survey)

Some years ago the senior author, in collaboration with Norah Dowell Stearns, undertook to make a monthly inventory of the water-supply of the Pomperaug River Basin, in Connecticut, from a study of data obtained by A. J. Ellis from 1913 to 1916. For this purpose approximate determinations or estimates were made of the ground-water runoff, that is, of the part of the daily discharge of the river that consisted of water derived from the zone of saturation by effluent seepage. The determinations or estimates were essentially based on the assumption that after a week of fair weather the storm-water was all discharged and that until the next rain the runoff was essentially all ground-water (U. S. Geol. Surv. Water-Supply Paper 597, pp. 107-116 and pl. 19, 1929). In the discussion of the methods and results of this investigation, the following statement was made (Water-Supply Paper 597, pp. 145-146):

> "In this investigation the estimates of ground-water runoff were based on the discharge of the Pomperaug at Bennetts Bridge--that is, on the discharge during the periods between rains, when there was virtually no direct runoff left in the stream-system. Much better results could be obtained by basing the estimates on periods beginning as soon after rains as all of the direct runoff has reached the streams. With this method the ground-water runoff during any particular day would be the total runoff minus the decrease in stream-storage. The decrease in stream-storage could be estimated by maintaining gages at several points on the trunk-stream and on selected tributaries and making surveys of the stream-system showing the approximate water-areas of different parts of the system at different gage-heights."

Recently a critical study has been made by W. G. Hoyt, L. L. Harrold, F. F. Snyder, and R. C. Cady of several possible methods for determining effluent seepage or ground-water runoff, the results of which have been published in Water-Supply Paper 772 (pp. 111-119). The subject is consequently much better understood now than it was at the time when the Pomperaug study was made. Nevertheless, all these other methods involve intangible assumptions and therefore they should at least be checked by the more tangible channel-storage method. The channel-storage method is based on the simple law that in any period when there is no overland runoff, that is, when no storm- or snow-water is running into the stream-system from the surface, the quantity of water derived by effluent seepage into a given stream-system equals the quantity of water discharged from the stream-system minus the decrease or plus the increase in channel-storage during the same interval. The law thus stated does not take into account the quantities of stream-water that are lost during the period by evaporation from the stream-system. If any part of the stream-system is influent, the law gives the net effluent seepage. It includes the seepage derived from bank-storage and perched ground-water.

Last year a beginning was made on a modest scale in the investigation of the channel-storage method, the stream-basin selected being that of Difficult Run, in Virginia, near Washington, D. C. It has not been possible to advance the investigation very far but certain definite results have been obtained.

Difficult Run rises near Fairfax, Virginia, and flows toward the northeast into the Potomac River. It has a drainage-area of about 58 square miles. Near its mouth the stream has cut a narrow gorge into the granite bed-rock, through which it descends from the plateau to the entrenched Potomac River below Great Falls. Back from the gorge the stream occupies a mature valley with graded sides and a fairly wide flood-plain. A substantial gaging-station with an automatic recorder has been installed near the mouth of the stream and one automatic rain-gage near the head. Three observation-wells with automatic recorders have been maintained in the basin since 1931 or 1932. Several additional shallow wells have been put down recently to study the relation of bank-storage and recharge on the flood-plain to stream-flow.

One channel-storage experiment has thus far been begun, and this is on a headwater-area of about one square mile near Fairfax. The stream-system of this area includes four small branches that join to form the head of Difficult Run. A gaging-station was installed on the trunk-stream, about 1200 feet above the point where Difficult Run crosses the highway leading from Fairfax to Winchester. The station is equipped with a V-notch weir and an automatic water-stage recorder. Measurements of channel-storage were made by means of 134 secondary gaging-stations. The trunk-stream and each of the branches was divided into 100-foot segments, and at the middle of each segment a secondary gaging-station was installed and a profile of the cross-section of the channel was made. Each gaging-station consists simply of a 2-inch by 2-inch stake driven into the bed of the stream so that the depth of water above the top of the stake can be measured with a scale. Secondary gages were installed and cross-sections of the channel were made as far upstream on each of the four branches as any stream existed. The volume of water in each segment at any time was computed in cubic feet by multiplying the area of the cross-section of the stream at the gaging-station for that segment, in square feet, by 100, and the channel-storage in the entire stream-system was computed as the sum of the volumes of water in all of the 134 segments. No account was taken in the computations of the dead storage below the level of the tops of the 2-inch by 2-inch stakes.

Series of measurements were made at the secondary gages at several different stages of the stream, in some cases by several persons working at the same time on different groups of stations in order to get all measurements of a series as nearly simultaneous as possible. A rating curve was then constructed in which the channel-storage was plotted against the stage of the stream at the weir. (See Fig. 1) Within the range of stage investigated the rating curve is essentially a straight line, evidently because the cross-sections of the channel between the stages covered are generally nearly rectangular. The channel-storage at different times was then computed from the record of the automatic water-stage recorder by means of this rating curve, and the discharge over the weir was computed from the same record by the usual methods of stream-gaging. Thus the process of computing effluent seepage became very simple.

The accuracy of the method depends largely on the degree to which the measured cross-sections represent actual average conditions. To obtain a check on the accuracy of the results, the channel-storage was computed by using only the data obtained at the stations having odd numbers and also by using only the data obtained at stations having even numbers. Curves were then drawn similar to the curve in Figure 1, in which the gage-height at the weir was plotted against the channel-storage for the odd-numbered segments, the even-numbered segments, and the combined odd- and even-numbered segments, respectively. Although the curves did not overlap, they had the same slope and therefore the change in channel-storage from one stage to another could be determined equally well from any of the three curves. None of the points departed from its particular curve by more than seven per cent, and the departures averaged less than two per cent. It is believed that by using the values as represented by the curve shown in Figure 1, the error involved in the determination of the change in channel-storage is less than five per cent.

It is planned eventually to apply the channel-storage method to the entire basin of Difficult Run by establishing gaging-stations on the trunk-stream from its head to its mouth and on certain of the larger tributaries. It is also planned to investigate the effects of bank-storage and perched ground-water upon the effluent seepage in the basin of Difficult Run.

The effluent seepage and its general relation to rainfall, ground-water levels, and runoff in the headwater-basin from June to November, 1935, are shown in Figure 2. In constructing the hydrograph for effluent seepage, a period of about 24 hours after the cessation of each rain, as recorded by the automatic rain-gage, has been allowed for overland runoff, although the overland runoff was generally all discharged into the stream-system in a much shorter period. For example, the overland runoff was observed to disappear within an hour of the cessation of each of two summer rain-storms of moderate intensity.

Rains occurring before June 15 caused floods and an increase in the effluent seepage, and also recharge in the vicinities of both the Swart and Bacon wells. From June 15 to September 1 the precipitation was not sufficient to influence the water-level in the Bacon Well, or to prevent a general decline of the water-level in the Swart Well and a general decrease in the rate of discharge of Difficult Run and of the effluent seepage. The general decline of the effluent seepage, however, is marked by minor fluctuations from day to day that follow closely the minor fluctuations in the water-level of the Swart Well, indicating a sensitive relation of the effluent seepage to the ground-water in the flood-plain, evidently in response to variations in the weather from day to day, such as light rains, sunshine or cloudy weather, and barometric fluctuations. The rain of 0.38 inch on July 13 increased the rate of discharge of the stream about 15,000 cubic feet a day (0.17 second-foot) and the rate of effluent seepage about 1500 cubic feet a day. At the same time the water-level in the Swart Well rose about 0.3 foot, which was probably somewhat more than could be produced merely by the cessation of transpiration. The rain of 1.18 inches on August 7, falling mostly during a period of four hours, increased the

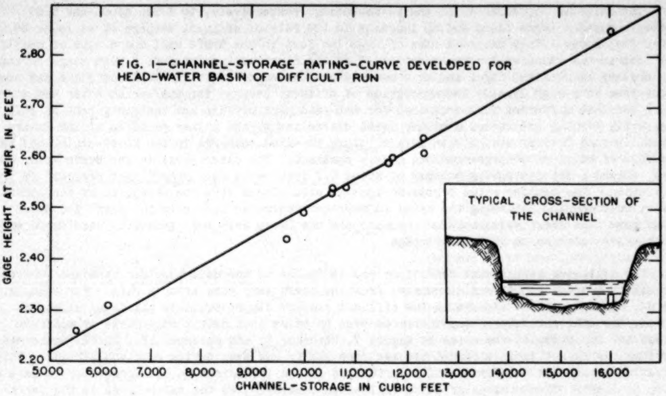


FIG. 1—CHANNEL-STORAGE RATING-CURVE DEVELOPED FOR HEAD-WATER BASIN OF DIFFICULT RUN

rate of discharge of the stream about 30,000 cubic feet a day (0.35 second-foot) and the rate of effluent seepage about 10,000 cubic feet a day. This rain also produced a rise of the water-level in the Swart Well of about half a foot but produced no rise in the Bacon Well. The water-level in the Swart Well and the rate of effluent seepage remained relatively high for several days after this rain.

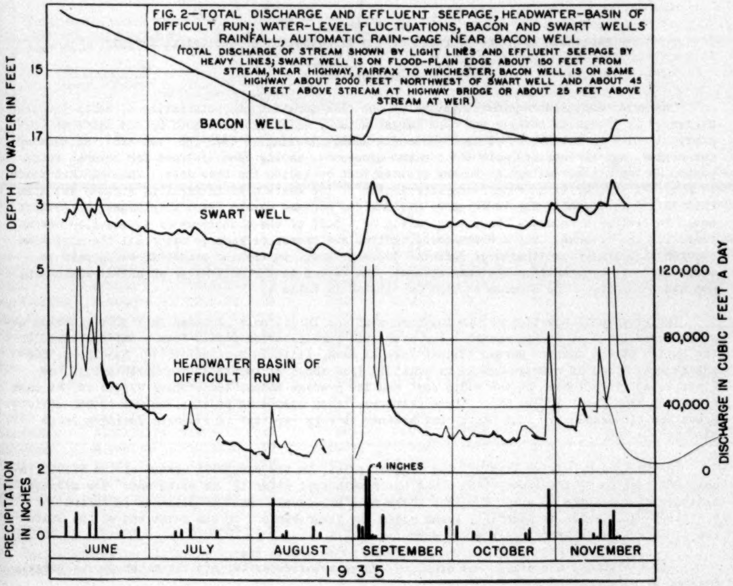


FIG. 2—TOTAL DISCHARGE AND EFFLUENT SEEPAGE, HEADWATER-BASIN OF DIFFICULT RUN; WATER-LEVEL FLUCTUATIONS, BACON AND SWART WELLS RAINFALL, AUTOMATIC RAIN-GAGE NEAR BACON WELL

(TOTAL DISCHARGE OF STREAM SHOWN BY LIGHT LINES AND EFFLUENT SEEPAGE BY HEAVY LINES; SWART WELL IS ON FLOOD-PLAIN EDGE ABOUT 150 FEET FROM STREAM, NEAR HIGHWAY, FAIRFAX TO WINCHESTER; BACON WELL IS ON SAME HIGHWAY ABOUT 2000 FEET NORTHWEST OF SWART WELL AND ABOUT 45 FEET ABOVE STREAM AT HIGHWAY BRIDGE OR ABOUT 25 FEET ABOVE STREAM AT WEIR)

DEPTH TO WATER IN FEET
15
17
3
5
BACON WELL
SWART WELL
HEADWATER BASIN OF DIFFICULT RUN
120,000
80,000
40,000
0
DISCHARGE IN CUBIC FEET A DAY
PRECIPITATION IN INCHES
2
1
0
4 INCHES
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
1935

The rains of September 4, 5, and 9--amounting, respectively, to 1.80, 4.00, and 0.80 inches--caused a large flood and an increase in the rate of effluent seepage of at least 36,000 cubic feet a day. They caused a rise of over two feet in the Swart Well and a rise of nearly one foot in the Bacon Well. The water-level in the Bacon Well maintained a high stage during the ensuing 18 rainless days, and as a consequence the water-table in the flood-plain was also maintained at a high level. The hydrograph of effluent seepage for the period after the storm has a somewhat different form from that for the late part of June and the early part of July, apparently grading off toward a higher level determined by the higher position of the water-table. During October enough rain fell to cause repeated recharge in the flood-plain, and hence the rate of effluent seepage remained nearly constant. The water-level in the Bacon Well, however, showed a net decline in October of about 0.7 foot, with only very slight response to precipitation. The October rains caused no considerable floods with the exception of the moderate one of October 29. Following the rains in November the water-levels in the Swart and Bacon wells rose--the Swart Well in quick response and the Bacon Well more gradually--and there was progressive increase in effluent seepage.

The following significant conditions are indicated by the data thus far obtained: First, the direct surface-runoff was discharged from the basin very soon after a rain. For example, one day after the flood on June 15 the effluent seepage almost equalled the total discharge. Second, the effluent seepage was increased even by rains that caused only small or moderate floods as, for example, the rains of August 7, November 7, and November 13. Third, there was considerable variation in effluent seepage from day to day even during rainless periods. This variation was caused chiefly by daily variations in the transpiration but apparently in part also by barometric fluctuations or other influences that affected the water-level in the Swart Well.

U. S. Geological Survey,
Washington, D. C.

FLOW-DURATION CHARACTERISTICS OF ILLINOIS STREAMS

J. H. Morgan

(Published with the approval of the Director, U. S. Geological Survey)

Introduction

The paper entitled "An investigation of the flow-duration characteristics of North Carolina streams," by Thorndike Saville and John Dargan Watson, which was published by the American Geophysical Union in its report of the Fourteenth Annual Meeting in 1933 (pp. 406-425), stimulated the writer, who is familiar with the streams discussed, having been assigned for several years to the United States Geological Survey offices that collected the base data. Knowing that there is a marked similarity in runoff-characteristics of the western North Carolina streams and also that fairly good similarity is shown by New England streams within reasonable zones, he felt it would be desirable to carry the investigation to a part of the country where stream-flow characteristics are diverse. The present investigation was therefore made to cover all the long-time records in Illinois on streams of definite drainage-area, particular attention being paid to comparisons of records from the same stream. The record on the Rock River at Afton, Wisconsin, was also included. The streams studied are listed in Table 1.

The geographic position of the fourteen stations in Illinois is shown in Figure 1, which also includes lines of normal annual temperature and precipitation copied from a map published by the United States Weather Bureau (Climatological data, Illinois Section, v. 36, No. 13, p. 53). The general trend of average annual rainfall is from about 31 inches at the north end of the State to about 45 inches at the south end, and the average annual temperature varies in the same direction from about 47° to 58°. These averages, taken over long periods, show a rather uniform gradation of weather over the State, but weather is very "spotty" in Illinois during a large part of the year.

The topography varies little. The highest point, in the northwest corner of the State, is only 962 feet above the lowest land along the Mississippi River in the south end. The average altitude of the State is about 600 feet above mean sea-level. Most of Illinois is farmed prairie-land. Timber is generally found along the river-banks. In the south end of the State the banks are overflowed nearly every year.

Soil-variations are wide. The north end has glacial deposits, and the south end is largely covered with impervious clay.

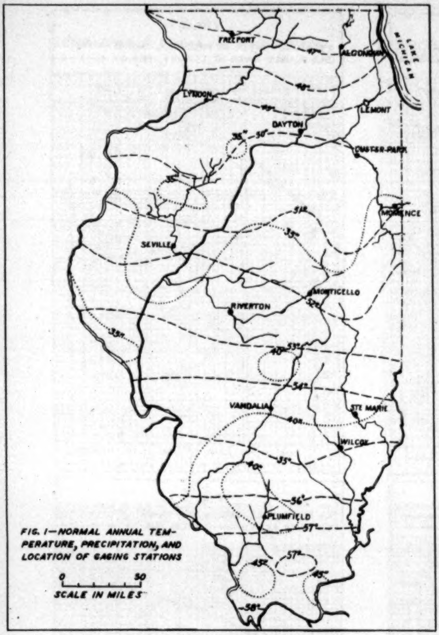


FIG. 1—NORMAL ANNUAL TEMPERATURE, PRECIPITATION, AND LOCATION OF GAGING STATIONS

The stream-flow data were collected by or under the supervision of the United States Geological Survey in cooperation with various State departments, the Army Engineers, and on the Fox River at Dayton with the North Counties Hydroelectric Company. Discharges for a few short periods of missing record for some of the stations have been estimated.

Tables of flow-deficiency have been worked up by using the total period as a basis and daily discharges under about 30 limits. The limits were selected so as to give a good distribution of points upon logarithmic coordinate paper. For example, the daily discharge of the Rock River at Lyndon was less than 700 second-feet for one day out of a total period of 6940 days, less than 800 second-feet for two days, less than 1000 second-feet for 36 days, and so on. The 1000 second-feet is 17.1 per cent of the mean discharge for the total period (5850 second-feet), and the 36 days is 0.52 per cent of the total period of 6940 days. These two percentages locate a point on the flow-deficiency curve. Instead of using that curve for percentages of discharge above the median flow, the flow-duration curve was used. The percentage of time-duration is obtained by subtracting the percentage of time-deficiency from

Table 1--Long-period records of stream-flow analyzed

River	Station[a]	Period of record	No. of years	Drainage-area in square miles	Mean flow in		Median flow, per cent mean flow	Range discharge, per cent mean flow 95 o/o of time	Spread, per cent mean flow 95 o/o of time
					sec-ft per square mile	per cent time-duration			
Rock	Afton	1915-32	18	3190	0.608	33.0	62.7		
Rock	Lyndon	1915-33	19	9010	0.649	32.5	68.4	22.6-410	387
Pecatonica	Freeport	1915-33	19	1330	0.727	28.3	66.0	27.7-412	384
Des Plaines	Lemont	1916-33	18	705	0.610	29.7	40.6	1.3-590[b]	589[c]
Kankakee	Momence	1916-33	18	2340	0.769	34.7	73.0	23.0-317	294
Kankakee	Custer Park	1916-33	18	4870	0.727	31.3	56.0	15.2-438	423
Fox	Algonquin	1916-25							
		1927-33	17	1340	0.617	32.6	64.4	13.5-393	380
Fox	Wedron-Dayton	1916-33	18	2570	0.607	32.8	61.2	15.2-417	402
Spoon	Seville	1915-33	19	1600	0.656	26.2	41.5	34.3-612	578
Sangamon	Monticello	1915-33	19	550	0.775	26.4	35.4	1.3-625	624
Sangamon	Riverton	1915-33	19	2560	0.709	26.3	37.3	1.3-580	579
Kaskaskia	Vandalia	1915-33	19	1980	0.523	26.2	36.4	1.6-600	598
Big Muddy	Plumfield	1915-33	19	753	1.01	25.8	13.2	0.3-747	747
Embarrass	Ste. Marie	1915-33	19	1540	0.812	27.0	36.3	1.8-590	588
Little Wabash	Wilcox	1915-33	19	1130	0.723	24.2	20.5	0.8-606	605

[a] All stations in Illinois, except Afton, which is in Wisconsin. [b] 650 per cent with flood-flow diversion at Willow Springs added. [c] 649 per cent with flood-flow diversion at Willow Springs added.

FIG. 2

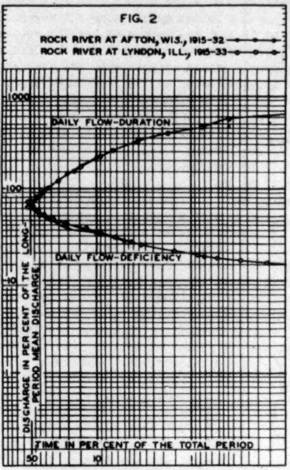


FIG. 3

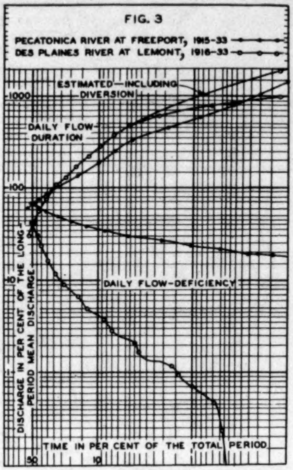


FIG. 4

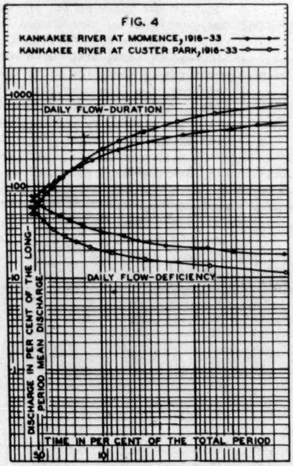
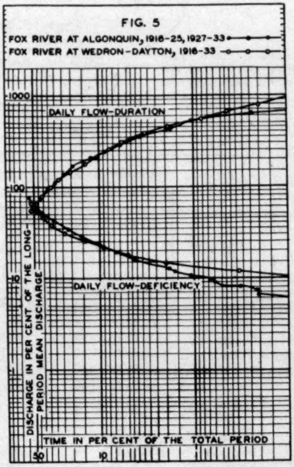


FIG. 5



100 per cent. Thus a graph having two limbs was plotted for each station, the lower limb reading percentage of time-deficiency and the upper limb reading percentage of time-duration. These are the most easily read parts of each curve, and they also show at a glance the range of discharge for the station by the distance between the limbs, referred to in this paper as the "spread."

In order to show all fifteen graphs on the same basis, it was necessary to have a chart with five cycles of logarithmic scale as ordinates and three cycles as abscissas. The only chart available was intended for the coordinates reversed, and therefore, in adapting it to this pur-

FIG. 6

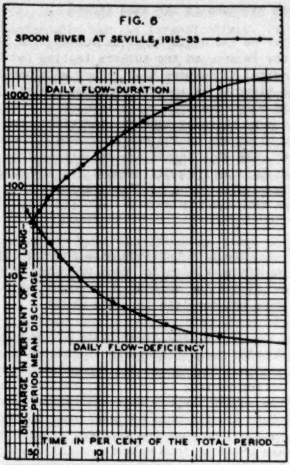


FIG. 7

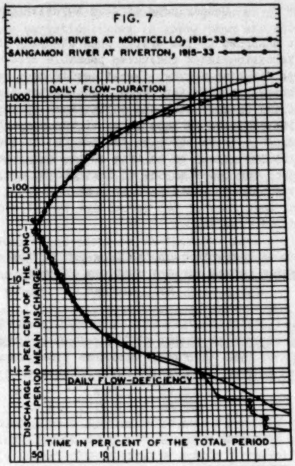


FIG. 8

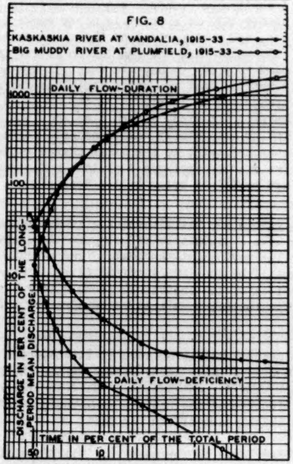
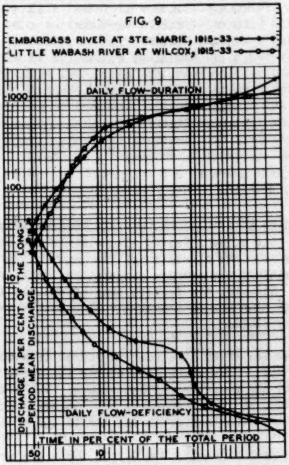


FIG. 9



pose, the abscissa-scale had to be read from right to left. For those accustomed to reading a "CI" scale on a slide-rule, this abscissa-scale will not be disconcerting.

These graphs of Figures 2 to 9 show that the differences in characteristics between the station records are very pronounced.

Comparisons of flow-duration curves of stations on the same stream

It occurred to the writer when studying the paper on the North Carolina curves that if a large variation-index indicated probable errors in the record, as the authors implied for the Hiwassee River at Murphy, then it would have been logical to compare that record with one on the same stream lower in the basin, such as the Hiwassee River at Reliance, Tennessee. Also, records of two or more stations on the same river should vary from each other as much as from the composite curve or perhaps more, if the composite is more reliable than the individual curves. However, this is not true of the records on the Rock River nor on the Fox River (see Tables 2 and 3) Though it may appear to be true on the Kankakee River, the wide percentage variations from the average of the two stations on that stream are explainable by real differences in flow-characteristics, due to definite causes. The writer is convinced also, from his familiarity with these records, that some of the percentage variations shown here are far greater than the possible errors in the records.

Table 2--A comparison of the long-period flow-duration curves for two stations on each river with their average

Per cent time-duration	Per cent variation each station from average of two stations on each river			
	Rock River	Fox River	Kankakee River	Sangamon River
2.5		∓2.96	∓15.9	± 3.74
5		∓2.68	∓12.0	∓4.07
7.5		∓0.76	∓ 8.67	∓5.92
10	±0.94	±0.88	∓ 6.67	∓4.50
15		±3.31	∓ 3.31	∓2.89
20	±0.92	±2.63	0.00	∓1.44
30	±2.05	0.00	± 3.63	0.00
40	∓2.54	0.00	± 7.22	0.00
50	∓4.13	±2.40	±13.2	∓1.12
60	∓3.19	±4.17	±15.7	∓3.45
70	∓1.95	±6.49	±20.5	∓5.00
80	∓5.21	±4.61	±21.2	∓2.70
90	∓1.50	±0.22	±23.1	±0.40
97.5		∓5.92	±20.4	∓4.67
Saville's variation-index from average of two stations		2.6	12.7	2.1

The flow-duration data for the station at Afton, Wisconsin, were prepared in another office for another purpose and therefore were not complete for this study.

On the Rock River there are many hydraulic power-plants, in Illinois and Wisconsin. Pronounced daily regulation occurs during periods of low flow, and this made the author suspect that the Lyndon record might consistently be inaccurate in one direction, because the mean daily gage-height was obtained from only two daily readings. A continuous recorder was installed in December 1933 at a point 16 miles above Lyndon, and a comparison of the two records for 1934 shows that the regulation is not the same from day to day--in fact, it was so diversified that the daily discharge-record at Lyndon was as likely to be too small as too large. The study showed also that the regulation was greatly damped between these two stations owing to the large channel-storage. The writer concluded that the Lyndon record was worthy of being called "good."

There is no seasonal storage between Afton and Lyndon, and the diversion of about 100 second-feet at Rock Falls, Illinois, is too small to have a noticeable effect upon the shape of the graphs. The character of the land is fairly similar throughout the basin. The average annual rainfall and average temperature increase somewhat from the source of the river to its mouth. However, the factors that affect the distribution of the individual flows with relation to their mean are so nearly the same at the two gaging-stations that their flow-duration curves are very similar.

The Fox River also has its source in Wisconsin, but not nearly so much of its drainage-area as the Rock. The upper half of the Fox River Basin contains many lakes, formed during the great ice-age, and some unreclaimed swamps. These lakes are used for recreation. There is little regulation of flow. Probably the largest amount is produced at the McHenry Dam, above Algonquin, by placing flash-boards on the dam in the spring and taking them off in the fall.

Between Algonquin and Dayton there are several power-dams of low head and insignificant storage-capacity. The Dayton Dam provides a usable capacity of about 9,000,000 cubic feet, which is almost negligible. The plant operates at the maximum power available with the run-of-river flow, 24 hours a day, up to its capacity.

To combine the Weldon record with the Dayton record, the limits of discharge of the groups for Dayton were reduced by the ratio of the drainage-areas of each station, and then used for the Weldon record. The drainage-area above Weldon is 2500 square miles.

Throughout the valley the characteristics of land and weather vary little. The most disturbing condition is that there are more lakes above Algonquin than below. However, the curves do not vary more than five per cent except for periods of low flow, when the evaporation from the lake-surfaces has its largest effect. Also, the variation-index is lower than any given for the western North Carolina curves.

The Kankakee River rises near South Bend, Indiana, and for the first 100 miles of its course to a point just above Momence, Illinois, flows through a marsh-and-lake country, of which about 1,000,000 acres has been improved by drainage and put into agriculture. Just above Momence is an outcrop of limestone extending across the valley and forming a natural dam to the drainage. About 40 years ago the State of Indiana cut a channel through the ledge to make possible the drainage-projects mentioned above. But a large amount of land in the marshes can be adequately drained only by cutting the ledge still lower. The slope of the River above the ledge averages only 0.83 foot to the mile, and there is still 47,500 acres above Momence subject to overflow.

The valley below the limestone-ledge is not subject to destructive floods. Here the River is wide, swift, and shallow, with an average slope of 2.8 feet to the mile. The bed is composed mostly of rock-outcrops, boulders, and gravel. Though there are four dams within this reach, at two of which power is obtained, the regulation is slight.

The average annual rainfall is about the same for all parts of the Kankakee Valley, and therefore the large differences between the two stations cannot be attributed to differences in rainfall. They can hardly be due to errors in the records. There remains only the conclusion that the differences must be caused by the wide differences in the land-characteristics discussed above.

The Sangamon River Valley above Riverton is homogeneous agricultural land of little variation in average annual rainfall. The one disturbing element to affect the similarity of the flow-duration curves for Monticello and Riverton is Lake Decatur, a water-supply reservoir formed by damming the Sangamon River at the city of Decatur. This reservoir has a drainage-area of 862 square miles, a capacity of 8,000,000,000 gallons, and a surface-area at crest-level of 2560 acres. It supplies filtered water to a population of 58,900, using 6,043,000 gallons a day, and raw water to a corn-products industry using 14,000,000 to 21,000,000 gallons a day. The stopping of the low flow at Decatur during the hot dry months since 1922, when the reservoir was completed, has its effect on the lower end of the Riverton duration-curve, even though the treated sewage effluent and the treated industrial effluent are returned to the River below Decatur. The seepage, evaporation, and transpiration losses are increased by this development, but their maximum effect is indicated by only five per cent difference at 70 per cent duration. The greatest effect of the reservoir seems to be the impounding of freshets at 7.5 per cent duration. The variation-index is the lowest of all.

From the comparisons of these four rivers the conclusion is inevitable that if all factors are homogeneous the flow-duration curves must agree within five per cent at all points and have a variation-index not greater than 2.0. This is a good indication of how closely a composite flow-duration curve should agree with a long-time flow-duration curve on any stream, if the composite curve is truly representative of that stream.

Comparisons of flow-duration curves with a composite flow-duration curve

A sight comparison of all 15 graphs indicates the undesirability of using one composite curve for all of Illinois. The graphs show a general gradation in features from north to south, which can be attributed to the gradation in average characteristics of climate and land described in the introduction to this paper. From such a comparison, however, the stations in northern Illinois, excluding the Des Plaines River at Lemont and using the average graph for the Kankakee River, appeared to be the most similar group in the State. Therefore, records from these stations were used to make a composite flow-duration curve. As the record at Afton, Wisconsin, agrees so well with that at Lyndon, it was intended to be used, but because all the flow-duration data were not available, it had to be omitted. A trial northern Illinois composite flow-duration curve was computed by averaging the curves for Lyndon, Freeport, Algonquin, Dayton, Momence, and Custer Park. This is not a true composite curve, because the curves were not weighted according to the number of years represented in each record, but as the records are of nearly the same length, this trial curve does not depart appreciably from a true composite. It will do very well to show how faithfully a composite curve can represent stream-flow duration in northern Illinois. The trial composite curve and its six constituents in the standard or orthodox form are presented in Figure 10.

In Table 3 every curve differs from the composite at two or more tabulated points by more than five per cent, and all but the Kankakee River average curve differ from the composite at

Table 3--A comparison of long-period flow-duration curves with a composite curve

Per cent time-duration	Ratio[a] discharge to mean discharge, long-time period	Per cent variation from trial northern Illinois composite curve												
		Rock River			Pecatonica River, Freeport	Fox River			Des Plaines River, Lemont	Kankakee River			Barrow's New England composite curve	Saville's western North Carolina composite curve
		Afton	Lyndon	Average		Algonquin	Dayton	Average		Momence	Custer Park	Average		
2.5	3.90		- 7.69		+ 5.64	+ 0.77	+ 6.93	+ 3.85	+51.3[b]	-18.5	+12.3	-3.08	-39.5	-20.5
5.0	3.05		- 6.56		0.00	+ 0.98	+ 6.56	+ 3.77	+47.6	-12.5	+11.5	-0.49	-27.5	-20.3
7.5	2.52		- 4.37		- 9.13	+ 3.57	+ 5.16	+ 4.37	+37.7	- 5.95	+11.9	+2.98	-17.5	-18.6
10.0	2.17	-1.34	- 3.22	- 2.30	-14.3	+ 5.53	+ 3.69	+ 4.61	+24.4	- 3.23	+10.6	+3.68	-10.1	-16.1
15.0	1.72		- 2.33		-17.4	+ 8.72	+ 1.74	+ 5.23	+11.6	+ 1.74	+ 8.72	+5.23	- 0.00	-11.0
20.0	1.45	-1.66	- 3.45	- 2.55	-15.9	+ 7.59	+ 2.07	+ 4.82	+ 0.69	+ 4.13	+ 4.13	+4.13	+ 4.14	- 6.9
30.0	1.07	+2.24	- 1.87	+ 0.19	- 9.35	+ 2.80	+ 2.80	+ 2.80	- 9.35	+ 6.54	- 0.93	+2.80	+10.3	+ 2.8
40.0	0.823	-1.94	+ 3.28	+ 0.61	- 4.01	- 0.36	- 0.36	- 0.36	-22.2	+ 8.14	- 6.44	+0.85	+10.6	+11.8
50.0	0.647	-3.09	+ 5.10	+ 1.08	+ 2.01	- 1.08	- 5.72	- 3.40	-36.6	+12.8	-13.4	-0.31	+ 9.74	+20.5
60.0	0.502	+2.79	+ 9.76	+ 6.17	+11.5	- 0.40	- 8.36	- 4.38	-56.2	+17.5	-14.3	+1.59	+ 9.56	+31.5
70.0	0.427	+6.09	+10.1	+ 8.20	+14.8	- 3.98	-15.7	- 9.84	-71.2	+17.1	-22.7	-2.81	+ 0.70	+31.1
80.0	0.350	+4.00	+15.7	+ 9.71	+22.3	- 9.14	-17.1	-13.1	-78.0	+14.3	-25.7	-5.71	- 5.71	+31.4
90.0	0.275	+18.9	+22.2	+20.7	+25.1	-17.8	-18.2	-17.8	-84.8	+16.4	-27.3	-5.46	- 5.45	+30.9
97.5	0.196		+15.3		+42.3	-31.1	-22.4	-26.5	-93.4	+17.3	-22.4	-2.55	+ 7.14	+27.6
Saville's variation-index from trial northern Illinois composite curve			8.2		13.5	6.1	8.6	7.3	44.8[c]	11.4	14.1	2.7	7.6	20.3

[a] Based on trial northern Illinois composite curve.

[b] 66.2 per cent with flood-flow diversion at Willow Springs added.

[c] 45.0 per cent with flood-flow diversion at Willow Springs added.

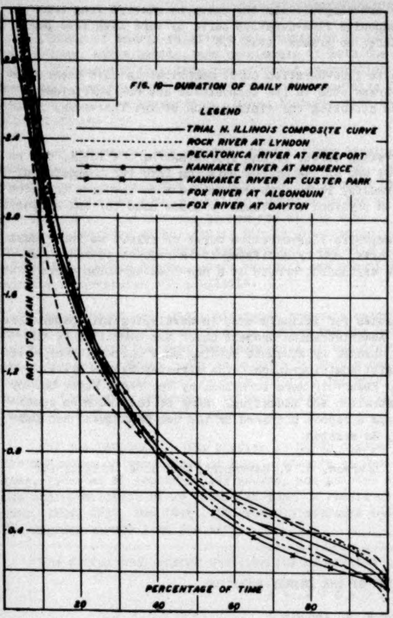


FIG. 10—DURATION OF DAILY RUNOFF

one or more tabulated points by more than ten per cent. However, Table 2 and the discussion of it tend to prove that a composite curve, if truly representative, will not vary from the individual record by as much as ten per cent at any point between the limits of duration, 2.5 and 97.5 per cent of time.

To show how much the composite flow-duration curves for New England and for western North Carolina differ from the trial composite curve for northern Illinois they have been included in Table 3. Their maximum differences are not as large as those on two of the northern Illinois individual curves.

The flow-duration curve that shows the best agreement with the trial composite is the average curve for the Kankakee River, but the foregoing discussion has shown that the application of the average curve to any part of the Kankakee River would be erroneous, and therefore the application of the trial composite curve would also be erroneous.

The flow-duration curve showing the widest disagreement with the trial composite is that for the Des Plaines River at Lemont. Although this record was frequently poor, the percentage differences shown in Table 3 far exceed the probable errors in the record for most of the tabulated points.

The Des Plaines Valley is adjacent to that of the Fox. These two valleys have similar topography, soil, and weather. The great difference between them is that the Fox River Basin is largely rural, whereas the Des Plaines River cuts across a wide suburban area adjacent to Chicago. Many dams have been built in this area to hold the water of the Des Plaines in long pools for recreation and beautification. Transpiration from the river-banks and evaporation from the water-surface have thereby been greatly increased. Consequently this stream has ceased to flow 0.135 per cent of the time. The writer witnessed no flow at the Lemont station. This is the only stream having as large a drainage-area that ceases to flow in northern Illinois. Moreover, urban and suburban areas are designed to drain very rapidly, and the runoff is increased by the roofed areas and the impervious street-surfaces. Both limbs of the Lemont graph have been shifted apart by these conditions, and the high percentages in Table 3 are rough indicators of the amount of the shifts.

Conclusions

(1) The writer agrees with Messrs. Saville and Watson that "the shape of a flow-duration curve, when plotted in terms of the mean flow, is little affected by the value of the mean for the period of record but is chiefly a function of the distribution of the individual flows with relation to the mean."

(2) Composite flow-duration curves, to have any sound value, must be built of records of streams that have similar distribution of the individual flows with relation to their mean.

(3) As the distribution of the individual flows with relation to the mean is affected by topography, arrangement of tributaries with regard to time of concentration of surface-flow, geologic structure, soil, vegetation, weather, and human developments related to flow of water, these seven physical conditions must be similar in kind and proportional amount in the drainage-areas of gaging-stations whose records are used in making the composite flow-duration curve.

(4) When the seven physical conditions are respectively the same, no station long-time flow-duration curve will differ from the composite flow-duration curve by more than five per cent at any point, nor will its variation-index be greater than 2.0.

(5) The trial northern Illinois composite flow-duration curve described in this paper does not have sound value, because the drainage-areas used in its composition are not sufficiently homogeneous in the seven physical conditions affecting the distribution of the individual flows with relation to their mean.

(6) Even if an ideal composite flow-duration curve, or one approximating the ideal, can be obtained, before it can be applied outside of one of the basins entering into its composition, with any assurance of arriving at correct results, it must be determined that the area to which it is to be applied is similar in those seven physical conditions to those used for the composite.

(7) It may be feasible to build up a composite flow-duration curve or select an individual flow-duration curve as a base for a certain area, and by modifying it in respect to the seven physical conditions by some method yet to be expounded, arrive at a new flow-duration curve that can be truly applicable to the area.

Acknowledgments--The flow-deficiency tables for Illinois used in developing this paper were prepared as a part of a Federal Civil Works Administration project under the direction of the writer during February and March, 1934, and checked by students working on a University of Illinois project under the Federal Emergency Relief Administration, also directed by the writer, during 1934-35. Facts regarding the Decatur Reservoir were furnished by the State Water-Survey Division of the Illinois Department of Registration and Education. Many of the facts on conditions in the Kankakee Valley were gleaned from a report prepared by the War Department and published as House Document 784, 71st Congress, 3d session.

The writer is indebted to Messrs. L. K. Sherman, R. W. Davenport, and G. W. Pickels for helpful criticism.

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EVAPORATION COMPUTED BY THE ENERGY-EQUATION

R. E. and R. W. Kennedy

[Explanatory note by N. W. Cummings--The original paper as submitted by Messrs. Kennedy contained an explanation of the terms of the energy-equation which duplicated in large measure that presented by me at the Pasadena meeting. At the suggestion of Mr. Harding these and some other parts of the paper have been deleted or condensed, and at the suggestion of R. E. Kennedy, I took a few liberties in making some other minor changes.

No computations have been changed or omitted, and it is believed that all are substantially correct, although time did not permit a complete check. There may be some slight mistakes in S for the pan. Mr. Kennedy has made use of Richardson's equation for back-radiation, using Fahrenheit temperatures and B.t.u's. per square inch for a 30.4-day month instead of Centigrade temperatures and calories per square centimeter per minute. This gives

$$B = (7.91\ T_w^4 - 6.89\ T_a^4)/10^9$$

in which T_w is the absolute temperature of the water-surface and T_a that of the air.

He also uses Fahrenheit degrees and inches of mercury in Bowen's equation which makes it take the form

$$R = 0.01[(t_w - t_a)/(p_w - p_a)]\ (P/29.92)$$

in which the subscripts w and a correspond to 1 and 2 in my paper.

If the energy-equations come into common use for estimating evaporation, a choice of units will eventually have to be made. For engineering purposes, the inch of depth and Fahrenheit degree have many advantages, but the case is not quite so clear for the pound, the B.t.u., and the square inch, since the gram-calorie and square centimeter have long been used for reporting insolation.

The phototube pyrheliometer referred to in the paper is the instrument described in the Transactions for the Sixteenth Annual Meeting of the American Geophysical Union, 1935 (pp. 515-519). Further work must be done on this apparatus, however, before perfect confidence can be placed in it.]

Introduction

A study of energy-relations was initiated in 1934 to compute the monthly evaporation from Devils Lake, North Dakota, and to compare it with the observed evaporation minus subsurface-inflow. Subtracting this from the computed evaporation yielded information about ground-water movement. Evaporation is here considered a positive function although it creates a downward movement of the water-surface. Other factors, such as rainfall, surface-inflow, and wave-action were accounted for.

Much assistance was obtained from a paper "Evaporation as a function of insolation" by Burt Richardson (Trans. Amer. Soc. C. E., v. 95, p. 996, 1931). The tabulations here presented are offered to illustrate the applicability and present practical limitations of the energy-method, which presents the most scientific approach to the subject yet proposed. The limitations are due to lack of data and can be removed at any time by making the requisite measurements. Computations are here shown, first, for an evaporation-pan with water-temperatures included in its record; second, for a nearby hypothetical lake with an average depth of 40 feet; third, for Devils Lake, North Dakota, where pan-data are absent and only Weather Bureau data and water-surface temperatures are available.

There are no mean daily air-vapor pressure records available, hence no monthly record. The Weather Bureau takes three readings during the day but none at midnight. The morning readings are thought to be the most representative of the diurnal range. It is very rough at best, but since the entire Bowen function amounts to only a small fraction of the total heat consumed, a range of 25 or 30 per cent in this function has only a second-order effect upon the final results. Richardson proposes a value of 22 per cent for R. It ranges from 15 to 28 per cent in Table 12 of his paper cited above.

The pan involved in the studies in North Dakota is the one maintained at the Great Plains Field-Station of the Bureau of Plant Industry at Mandan. It is 6 feet in diameter, 24 inches deep, inserted 20 inches in the ground, and painted black on the inside. It was assumed to have the characteristics of an insulated pan. A record of water-temperatures was kept for three seasons, 1914, 1915, and 1916. The montnly averages indicate that the water was in every case a few degrees warmer than the air.

The fundamental energy-equation may be written

$$I = LE + B + S + LER + C \tag{1}$$

The nomenclature used is the same as that used in the paper by N. W. Cummings, printed later in these Transactions, presented at the meeting of the Section of Hydrology in Pasadena, February 1, 1936.

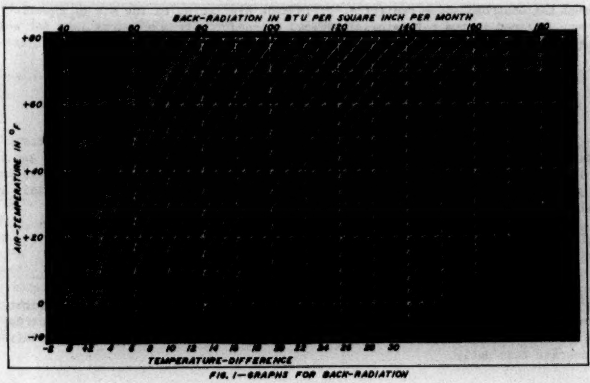

FIG. 1—GRAPHS FOR BACK-RADIATION

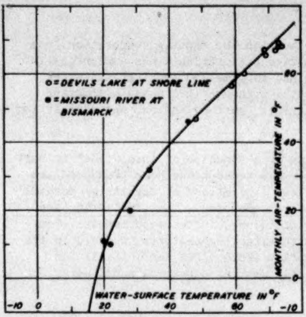

FIG. 2—EVAPORATION FROM A HYPOTHETICAL LAKE AT MANDAN, NORTH DAKOTA

AIR-TEMPERATURE IN °F	0	1	2	3	4	5	6	7	8	9
-0	17	17	17	17	16	16	16	16	15	15
0	17	18	18	19	19	19	19	20	20	20
10	21	21	21	22	22	23	23	24	24	25
20	25	26	27	27	28	28	29	30	31	31
30	32	33	34	34	35	36	37	38	39	40
40	41	42	43	44	45	46	47	48	49	50
50	51	52	53	54	55	56	57	58	60	61
60	62	63	64	65	66	67	68	69	71	72
70	73	74	75	76	77	78				

Outline of computations

The mathematical operations involved are summarized as follows:

(1) Multiplication of inches lost per month from the pan water-surface, by 38.3 B.t.u.'s per cubic inch gives the evaporation-heat, LE, in B.t.u.'s per square inch. If this does not at first seem clear, it may be helpful to regard depth as cubic inches per square inch.

(2) When the pan is not used, the back-radiation, B, is taken from the curves on Figure 1, which is based on Richardson's equation. In applying this chart, use is made of the temperatures given in columns 1 and 2 which, as the tables show, are nearly the same for all three bodies of water. In actual fact, the water-temperature would probably be higher for both the hypothetical lake and Devils Lake than for the pan, but available data are not sufficiently complete to show this.

When the pan is employed, B is usually interpreted as the difference in back-radiation for the two bodies of water which is computed according to the method explained on page 529 of the paper by Cummings and Richardson (Evaporation from lakes, Phys. Rev., v. 30, pp. 527-534). In the present paper both the chart and the pan were used, but the result is practically the same as for the other procedure.

(3) Direct heating, S, in B.t.u.'s per square inch equals the temperature-change of the water-body during the month, in degrees Fahrenheit multiplied by the number of pounds in a water-column having an area of one square inch, and a length equal to the average depth of the lake.

(4) Convection, LER, may be taken as 22 per cent of the evaporation-heat or R may be computed from Bowen's equation given above if the data in columns 1, 2, 3, and 4 are available.

(5) Conduction, C, is ignored in this study.

(6) When the absorbed solar radiation, I, is made available, by the aid of equation (1) or by the method outlined in the following paragraph, evaporation from a nearby lake for which water-temperatures are recorded may be computed from formula (1) above, rearranged thus

$$E = [I - (B + S + C)]/L(I + R) \qquad (2)$$

Computation without pan-evaporation data

If no record of pan-evaporation is available, then the solar radiation at the Earth's surface, I, must be computed by applying two correction-factors--the cloudiness-factor and the atmospheric depletion-factor--to the solar radiation at the exterior of the Earth's atmosphere, I (ex) as given in Table 12 of Richardson's paper previously cited. The values in this Table must be multiplied by 0.78 to yield B.t.u.'s per square inch per 30.4-day month.

The cloudiness-factor, F, is computed from Kimball's formula

$$F = 0.22 + 0.78\ s$$

in which s is the per cent of daily sunshine recorded for the month at the nearest first-class Weather Bureau station. The sunshine-recorder classifies as cloudy any moment of the day when the Sun is obscured even though it be by a mere skiff of a cloud. Hence average monthly values are more accurate than daily.

Table 1--Computation of absorbed solar radiation, I

[Data obtained from ground-pan record of Bureau of Plant Industry at Mandan, North Dakota; latitude 47° 00', elevation 1750 feet; pan 6 feet by 24 inches, 20 inches in ground with 20 inches of water-depth; normal barometric pressure is 28.06 inches; Weather Bureau station at Bismarck, North Dakota, is five miles east.]

Month	Observed data					Computed functions										
	Temperature		Vapor-pressure		Evaporation	Miscellaneous					Distribution absorbed solar radiation					
	t_w (1)	t_a (2)	P_w (3)	P_a (A.M.) (4)	E (5)	R (6)	I(ex) (7)	s (8)	F (9)	p(rho) (10)	LE (11)	B (12)	S (13)	LER (14)	C (15)	Sum = I (16)
1915	°F	°F	inch	inch	inch		btu	per cent			btu	btu	btu	btu	btu	btu
March	(29)															
April	(54)	52	0.417	0.226	4.85	0.100	605	61	0.695	0.691	185	79	9	18	x	291
May	53	51	0.402	0.255	3.86	0.128	728	39	0.524	0.650	148	78	3	19	x	248
June	61	59	0.536	0.359	5.38	0.106	780	53	0.634	0.638	205	83	5	22	x	315
July	67	63	0.661	0.441	5.42	0.171	753	56	0.656	0.694	207	95	4	36	x	342
August	71	65	0.757	0.444	5.47	0.181	659	75	0.805	0.659	209	105	-3	38	x	349
September	59	56	0.499	0.319	3.65	0.157	459	55	0.649	0.800	139	86	-9	22	x	238
October	(47)															
Totals					28.63	0.843				4.132	1093	526	9	155	x	1783
Averages						0.140				0.690	182	87	2	26	x	297
Per cent											62	29	0	9	x	100

Column 7 taken from Table 12 "Evaporation as a function of insolation" by Burt Richardson (Trans. Amer. Soc. C. E., v. 95, p. 996, 1931; column 8 taken from Weather Bureau data at station Bismarck, North Dakota; column 13 computed thus as for April: Temperature-change = (25 - 1)/2 = 12.°0; 12° x 0.722 lb. = 9 Btu.

[x]C is assumed negligible.

Table 2--Evaporation computed for a hypothetical lake at Mandan, North Dakota, for average depth 40 feet and bottom-temperature assumed constant at 40° Fahrenheit

[This tabulation shows that when the surface-temperature of the lake is nearly the same as that of the pan and the constant C is neglected, the annual evaporation for the two bodies of water is practically the same but the distributions throughout the year are quite different; in the spring the loss from the lake is less, and in the fall greater than from the pan.]

Month	Temperature		Vapor-pressure		R	Computed evap'n E	Distribution absorbed solar radiation					
	t_w (1)	t_a (2)	P_w (3)	P_a(A.M.) (4)	(5)	(6)	LE (7)	B (8)	S (9)	LER (10)	C (11)	Sum = I (12)
1915	°F	°F	inch	inch		inch	Btu	Btu	Btu	Btu	Btu	Btu
March	(30)											
April	53	52	0.402	0.226	0.053	3.03	116	74	95	6	x	291
May	52	51	0.387	0.255	0.071	3.41	131	73	35	9	x	248
June	61	59	0.536	0.359	0.106	4.15	159	83	56	17	x	315
July	65	63	0.616	0.441	0.107	5.44	208	85	26	23	x	342
August	67	65	0.661	0.444	0.086	7.14	274	87	-35	23	x	349
September	57	56	0.465	0.319	0.064	5.77	221	77	-74	14	x	238
October	(50)											
Totals					0.487	28.94	1109	479	103	92	x	1783
Averages					0.081		185	80	17	15	x	297
Per cent							62	27	6	5	x	100

Column 1 is taken from table on Figure 2; columns 2, 4, and 12 are the same as columns 2, 4, and 16, respectively, in Table 1; column 9 is computed by assuming a straight-line temperature-gradient from the surface to the bottom.

[x]C is assumed negligible.

Table 3--Evaporation computed for Devils Lake, North Dakota

[Latitude 48° 07', elevation 1420 feet, depth 18.5 feet, area 53 square miles; Weather Bureau station is five miles northeast]

Month	Temperature		Vapor-pressure		Miscellaneous functions					Computed evap'n E (10)	Distribution absorbed solar radiation					
	t_w (1)	t_a (2)	P_w (3)	P_a (4)	R (5)	I(ex) (6)	s (7)	F (8)	p(rho) (9)		LE (11)	B (12)	S (13)	LER (14)	C (15)	Sum = I (16)
1915	°F	°F	inch	inch						inch	Btu	Btu	Btu	Btu	Btu	Btu
March	28															
April	49	48	0.347	0.190	0.061	599	51	0.618	0.65	1.90	73	72	92	4	x	241
May	52	51	0.387	0.219	0.057	727	52	0.626	0.65	4.84	185	74	26	11	x	296
June	56	55	0.448	0.316	0.072	780	41	0.540	0.65	3.80	146	76	46	10	x	278
July	64	62	0.595	0.394	0.094	752	57	0.665	0.65	4.72	181	85	42	17	x	325
August	67	65	0.661	0.366	0.065	654	62	0.704	0.65	5.91	226	87	-30	15	x	298
September	56	55	0.448	0.293	0.061	452	45	0.571	0.65	4.23	162	76	-80	10	x	168
October	46															
Totals										25.40	973	470	96	67	x	1606
Averages											162	78	16	11	x	268
Per cent											61	29	6	4	x	100

Column 1 taken from table on Figure 2; column 6 taken from Table 12 "Evaporation as a function of insolation" by Burt Richardson (Trans. Amer. Soc. C. E., v. 95, p. 996, 1931); column 9 computed from more extensive data than shown in Table 1; column 13 computed on basis of uniform water-temperatures as found by soundings.

[Note--Since computed evaporation, April 19, 1915 to October 2, 1915 = 24.50 inches and observed evaporation minus subsurface-inflow = 23.50 inches; subsurface-inflow = 1.00 inch = 8.6 cubic feet per second. If 70 per cent is used for p(rho), column 9, the computed evaporation equals 28.44 inches and subsurface-inflow for the period April 19 to October 2, 1915, equals 31.5 cubic feet per second.]

^{x}C is assumed negligible.

Need of pyrheliometric data

The atmospheric depletion-factor, p(rho), must be assumed in lieu of observed data. Richardson suggests a value of 70 per cent. That computed in Table 1 varies from 64 to 80 per cent. One suspects that such a range is due in part to roughness of data. A record with a phototube-pyrheliometer would enable one to check these computed values. Without it only average values can be used. This limitation introduces considerable discrepancy for individual months to say the least.

With these two corrections, solar radiation at the Earth's surface may be computed thus

$$I = I(ex) \times F \times p(rho)$$

Table 1 is submitted to show the computation of the absorbed solar radiation, I, from pan-data.

Table 2 shows the computation of evaporation from an assumed nearby lake, the monthly water-temperatures for which are taken from Figure 2. It indicates that so far as the annual result is concerned a coefficient of unity occurs when the conduction-factor, C, is omitted and when the temperatures are not widely different for pan and lake.

Table 3 shows evaporation computed for Devils Lake, where only water-temperatures from Figure 2 are available. It also shows that an increase in the value of p(rho) from 0.65 to 0.70, which is eight per cent, increases the computed evaporation by 16 per cent and the subsurface-inflow by over 300 per cent.

Each Table shows the relative per cent of heat diverted to each one of the channels indicated by the right-hand member of equation (1).

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NOTES ON THE TRANSPORTATION OF SILT BY STREAMS

Morrough P. O'Brien

Several recent papers on the transportation of bed-load and suspended material by flowing water have included assumptions or theories which are in disagreement either with fundamental mechanical principles or with experimental results. Since a number of experimental programs are in progress, a discussion of these problems may be of some value in the interpretation of results.

Gilbert has described the stages in the transportation of silt as beginning with rolling motion which develops into saltation and finally becomes suspension. Attempts to separate bed-load from suspended material must depend upon an arbitrary definition and in the following notes the two phases are treated concurrently.

Basic equations--The solution of dynamical problems requires one or more of the following relationships: Force = mass X acceleration; impulse = change of momentum; work = change in mechanical energy. Force and impulse are vector-quantities and the equations must be written for a certain direction, while work is a scalar quantity. Selection of the equation to use in the solution of a particular problem is a matter of convenience, but all three must be satisfied in every case, a fact which appears to have been lost sight of in some treatments of the problem.

Applied to the uniform, steady flow of water in an open channel, the force-equation is

$$w\,A\,S - T_0\,p = 0 \tag{1}$$

Here, w is the weight of water per unit-volume, A is the area of the cross-section, S is the slope (the bottom, water-surface, and energy-line are parallel), and T_0 is the average tractive force per unit-area around the perimeter p. The flow is not accelerated and the right-hand side of equation (1) is zero. Solving for T_0

$$T_0 = w\,(A/p)\,S = w\,R\,S \tag{2}$$

Equation (2) applies to turbulent or viscous flow, with or without silt-transportation and the tractive force T_0 is in no sense fictitious. Regardless of the mechanism of energy-dissipation, an average traction T_0 must be exerted by the bed to prevent acceleration. If the channel is wide or if the roughness of the bed is very great in relation to that of the sides of the channel, equation (2) becomes approximately

$$T_0 = w\,D\,S \tag{3}$$

It is particularly noteworthy that equation (2) gives the average tractive force around the wetted perimeter. In laboratory work, the side-walls of the flume are usually less rough than the bottom, and the average tractive force across on the bottom may be very nearly that given by equation (3).

Derivation of the equation for the tractive force can best be accomplished through the medium of the work-energy equation. To simplify the treatment, the channel will be assumed to be wide in proportion to the depth. In a layer of thickness dz, the dissipation of available mechanical energy per unit-area per second is T(du/dz)dz. Here, T is the tractive force and u is the velocity at point z. Under the assumed conditions, $T = T_0(Z/D)$ and the velocity may be represented as $U = U_m f(z)$. Here, U_m is the mean velocity as defined by

$$U_m = (1/D)\int_0^D U_m f(z)dz \quad \text{or} \quad (1/D)\int_0^D f(z)dz = 1$$

The total energy dissipated per unit-area of bed is

$$W = -\int_0^D T_0(z/D)\;U_m\;[df(z)/dz]\,dz = -T_0U_m\int_0^D Zdf(z)/D$$

Integrating by parts

$$W = -T_0U_m\,[Zf(z)/D] - (1/D)\int f(z)dz\Big]_0^D$$

At Z = D, f(z) = 0, since the velocity must be zero at the bed, and the second term has a value of unity so that

$$W = T_0 \times U_m \tag{4}$$

A more complete investigation for a channel of any shape shows that the total energy-dissipation around the periphery and for unit-length in the direction of flow is $T_0 pU_m$.

Equation (4) expresses the rate of loss of energy by the moving stream and may be equated to the decrease in energy between any two sections. Considering a width b and length d , the loss is $(b \cdot T_0 U_m d\ell)$ per second. The available mechanical energy per unit-weight is

$$E = Z + D + \alpha\,(U_m^2/2g)$$

The decrease in the energy transported by the stream in the length $d\ell$ is $wU_m bD \cdot dE$. Equating the two expressions,

$$bT_0 U_m d\ell = wU_m bDdE$$

But $dE/d\ell$ is S, the slope of the energy grade-line and hence

$$T_0 = w\ D\ S \tag{3}$$

For a channel of any shape, the equation for the energy-balance is

$$T_0 pU_m d\ell = wU_m AdE \qquad T_0 = w\ R\ S \tag{2}$$

In other words, the tractive force which is a measurable quantity is directly related to the dissipation of mechanical energy and therefore to the slope of the energy grade-line, which is the slope to be used in all of the friction-equations.

Velocity-gradient and tractive force--The quantity T_0, as used in equation (2), is an average value over the periphery of a cross-section. It is evident that considerable deviations from the average may occur and this probably accounts for the fact that some experimenters have found a better correlation on the basis of wDs rather than wRs. A serious objection to the use of either of these forms in the correlation of data is that a finite reach of uniform section is necessary for the determination of s. Such conditions may be obtained in the laboratory, but they seldom exist in nature and a more detailed study of the phenomenon appears to be necessary if the experiments in the laboratory are to be used for estimating the transportation in natural streams. Even application of field-measurements on the rate of transportation to other streams will require much more than a knowledge of slope, mean velocity, average depth, and so forth, because the movement is not a linear function of these variables. Considering bed-transportation particularly, it appears to be necessary to relate the transportation to the local hydraulic conditions rather than to the average over a cross-section if the results are to be generally applicable.

The theory of turbulent flow, as developed by von Karman, Prandtl, and G. I. Taylor, appears to offer a solution to the problem of the proper correlation and generalization of data in the field and laboratory. According to this theory, the tractive force in a fluid of uniform density may be computed from two points on the velocity-gradient. As applied to pipes or very wide channels, the form of this equation is

$$T_0 = \rho K^2(u_2 - u_1)^2 / \left\{\log\left[1 - \sqrt{1 - (z_1/z_2)}\right] + \sqrt{1 - (z_1/z_2)}\right\}^2 \tag{5}$$

The quantity K is a universal constant applicable to homogeneous fluids having a value of about 0.4. Some modification of K is to be expected to result from the presence of silt in suspension and the variation can probably be related to the vertical variation in density. As regards bed-movement alone, the value of K obtained from measurements in pipes appears to apply to open channels. Experiments indicate a reasonably good agreement between the values of T_0 computed from equation (5) and the average value of w R S. Further experiments on this point are necessary and it is particularly important that T_0 be measured directly by weighing.

Equation (5) includes only the difference in velocity at two points and so does not provide a means of predicting the absolute velocity in terms of a known T_0. Experiments on artificially roughened pipes show that equation (5) applies to the turbulent core of the flow and that the effect of an increase in the roughness is to reduce all velocities by the same amount. Nikuradse obtained the equation

$$u = \sqrt{T_0/\rho K^2}\ [5.75 \log_{10} (z/k) + 8.5] \tag{6}$$

Here, K is the diameter of the sand-particles attached to the wall of the pipe and the constant 5.75 corresponds to K = 0.40. Some doubt has been indicated by von Karman as to the validity of equation (6), but it seems likely that this or a similar equation will result from additional experiments.

The importance of these theoretical equations is that from equation (5) it should ultimately be possible from measured velocity-distributions to compute the tractive force at all points around the periphery and from equation (6), or its equivalent, to compute the effective roughness at the same points. Simultaneous measurement of the rate of bed-transportation at a number of points around the periphery would then provide a complete set of data for analysis. Whether or not the tractive force is found to provide a proper basis for correlation of data on the rate of movement, measurement of the velocity-gradient immediately adjacent to the bed appears to be a necessary feature in the generalization of data on transportation both as bed-load and in suspension.

Critical tractive force--The tractive force given by equations (2) or (3) is a force which must be transmitted undiminished into the stream-bed and is therefore very nearly the tangential stress exerted upon the surface-layer of particles. The forces on individual sand-grains will vary with their exposure, but the average over a large area must be very nearly T_0. For any grain to be dislodged and start to move, it is necessary that the force exerted on it be sufficiently large to overcome the static friction and to roll it over the adjacent grains. Consequently, for a particular size, shape, and specific gravity, the grains remain stationary until T_0 exceeds a certain value known as the critical tractive force. Attempts have been made to represent the critical conditions on the basis of the mean velocity alone and of the product sq but it appears to be more reasonable to assume that the tractive force alone is the controlling factor in dislodging material.

Experiments by Kramer and Indri on the critical tractive force are interesting in connection with the theory of turbulent flow. Kramer (Proc. Amer. Soc. C. E., April 1934) found that the critical tractive force increased linearly with the quantity $k[(\rho_1 - \rho)/M]$, where k is the mean grain-size, ρ_1 and ρ are the specific gravities of sand and water, and M is a factor representing the shape of the sieve-analysis. However, the points broke away from his straight-line relationship above a certain value of k. Additional experiments by Indri (L'Energia Elettrica, v. XI, December 1934) in the region above the "break" in Kramer's curve, showed that the points followed another straight line but at a steeper angle. The interesting feature of these data is that the "break" between the two straight lines occurs very nearly at the grain-size at which the influence of the roughness begins to be effective. According to von Karman (J. Aeronaut. Sci., v. 1, No. 1, January 1934), the roughness of pipes begins to affect the friction-coefficient when $k/\delta = 1/4$ and the friction-factor becomes constant for $k/\delta > 6$. Here, δ is the theoretical thickness of the layer in laminar flow and probably should be regarded as a fictitious dimension to be computed from

$$\delta = 11.5\nu/\sqrt{T_0/\rho}$$

Here, ν is the kinematic viscosity. Values of the ratio of (k/δ) for a few of the points given by Indri appear in Table 1. The materials were sand-mixtures which would not present a uniform roughness and complete regularity is not to be expected but the results show rather clearly that, until the size of the sand-grain is of about the same magnitude as the theoretical thickness of the laminar layer, the critical tractive force follows one equation while for larger grain-sizes it follows another relationship. The results indicate the importance of studying the conditions existing very close to the sand-surface.

Table 1

Sand	T_0	δ	k	k/δ	Curve
	(lbs/ft^2 x 10^4)	(ft x 10^3)	(ft x 10^3)		
1	36.9	2.87	0.531	0.18	Lower
2	63.6	2.19	0.778	0.36	Lower
F	57.5	2.30	1.50	0.66	Lower
M	119.	1.59	1.375	0.87	Lower
A	154.	1.41	2.52	1.79	Lower
D	232.	1.15	3.68	3.20	Upper
C	540.	0.75	6.66	9.83	Upper
4	835.	0.60	6.56	10.9	Upper
V	1000.	0.55	8.70	15.6	Upper

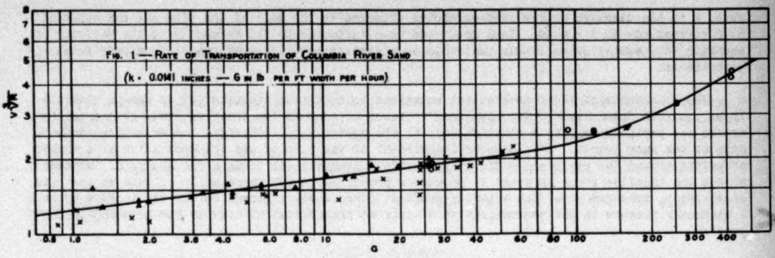

Fig. 1—Rate of Transportation of Columbia River Sand

(k = 0.0141 inches — G in lb per ft width per hour)

Rate of bed-movement--After the critical tractive force is exceeded, the bed-materials move and, as the factors controlling motion are increased, some of the particles begin to saltate, and finally, when the trajectories become sufficiently extended, a condition of suspension is said to exist. Concurrently, with the suspension there is movement in the immediate vicinity of the bed and it appears likely that this movement is always an appreciable percentage of the total transportation. Theory indicates and direct measurements appear to confirm the conclusion that the concentration of silt increases very rapidly near the bed. The vertical variation in density is a function of the fall-velocity of the material in suspension and with very fine sediments it may be that bed-transportation is negligible but this remains to be demonstrated.

Nearly all of the experimental work on bed-transportation has been done under conditions which did not result in appreciable suspension and there is therefore little basis for estimating the bed-transportation accompanying suspension. Experiments on this problem should aim at suspension of a fraction of the bed itself.

Correlation of experimental data on the rate of bed-transportation has been attempted in a number of different ways. Average velocity is the simplest variable to use but the results are scattered if there is a considerable variation in depth. The average tractive force, T_0, has been used with some success. The product sq, which is approximately equal to T_0U_m, has been used by Schoklitsch, MacDougall, and others. Both of these criteria suffer from the disadvantage that s can be determined only in a finite reach of channel of constant section and therefore application to field-conditions is difficult. The average tractive force may be computed approximately from Manning's equation as

$$T_0 = w\, n^2\, U_m^2/(1.49)\, R^{1/3} \tag{7}$$

The local tractive force at any vertical section may be approximated by substituting the local depth for R. However, equation (7) requires an assumption regarding the friction-coefficient n, which depends not only on the grain-size but on the ripple-formation as well.

A reasonable assumption appears to be that the bed-movement depends only upon the velocity-gradient immediately adjacent to the bed. Furthermore, the ripple-formation and hence the value of n is not an independent variable, but depends upon the characteristics of the grains and the rate of movement. Consequently, on the basis of equations (5), (6), and (7), the rate of bed-movement may be expected to be determined by those overall variables which control the velocity-gradient at the bed and, of these variables, the most readily available at any section of a stream are U_m and R or D. Figure 1 shows experimental results on a sand dredged from the lower Columbia River. The data were plotted also against U_m, sq, wRs, and wDs, and all of these methods showed much greater scattering of the points. The same method of plotting will be applied to other data and it may be found that the exponent of R must be altered.

Use of U and R as a means of correlating data is not regarded as a substitute for a detailed investigation of velocity-gradients near the bed, but the results shown appear to confirm the view that the velocity-gradient at the bed is the important factor in bed-transportation.

If one regards bed-movement as a stream of material moving past any section at a rate dependent upon the local hydraulic conditions, then scour or deposition are not superimposed phenomena, but are merely the result of variations in the rate of transportation. If the hydraulic conditions and the geometry of the bed are such that the rate of transportation increases downstream, scour results and vice versa.

__Dissipation of energy__--It has been shown previously that the total dissipation of energy is $T_0 \rho U_m$ in both laminar and turbulent flow with or without sediment in suspension but no mention was made of the details of such dissipation. Since turbulent flow usually exists in open channels, the discussion will be limited to this type of flow.

Experiments indicate that normal fluids, such as air and water, are at rest relative to any solid boundary with which they are in contact and that adjacent to the solid boundary there is a layer of fluid in laminar motion. For smooth pipes, the thickness of this layer has been indicated previously. In spite of the fact that this layer is very thin, a large percentage of the total energy-dissipation occurs within it. Considering smooth pipes, the relationship is

$$E_\delta / E = U_\delta / U_m$$

Here E_δ is the energy-dissipation in unit-area of the laminar layer per second, E is the total dissipated per unit-area of bed, and U_δ is the velocity at edge of the laminar layer. Since U_δ / U_m is of the order of 0.5, direct conversion of mechanical energy into heat is not negligible in the case of smooth pipes. A rough surface such as a sand-bed tends to break up the laminar layer, but the area of contact is greater and it is difficult to estimate whether the dissipation is greater or less than for a smooth pipe.

The mechanism by means of which the remainder of the energy is dissipated is not known in detail but experiments suggest that the very steep velocity-gradients near the solid boundaries give rise to rotating fluid-masses which are thrown off at random into the main body of the fluid, resulting in turbulence. The total kinetic energy added to this motion per second by each unit-area of the bed is $(E - E_\delta)$, and if equilibrium has been attained this is also the rate at which the energy is being dissipated by viscosity in the interior of the fluid. As the fluid moves about, it carries with it such properties as temperature and salinity and a diffusion of these properties results. In the case of sediment, the grains do not move with the fluid but fall downward through it, and it is necessary that the upward fluid-velocities exceed the downward particle-velocity if suspension is to occur regardless of how much energy is available to cause suspension.

Assuming that a suspension exists, the rate at which potential energy is being dissipated per unit-area of bed is

$$\int_0^D C(\rho_1 - \rho) m \, dz$$

Here C is the fall-velocity and m is the concentration. However, one may not regard this energy as a term to be added to the energy which would be dissipated in clear water at the same mean velocity and depth. It is probably more nearly correct to regard the energy dissipated by the falling silt as merely an added step in the dissipation of the same amount of energy. However, the presence of the silt results in a vertical variation in density which tends to suppress the turbulence and hence the presence of the silt probable results in a change in the nature of the flow rather than in a simple addition to the energy-dissipation. That the latter view is incorrect is shown by the fact that in the transportation of sand through pipe-lines, the loss of head (mechanical energy per unit-weight of mixture) is __less__ with sand in suspension than at the same mean velocity with clear water.

__Distribution of sediment__--The random transfers of fluid in the turbulent core of the stream result in an average distribution of sediment such that the average density increases downward. W. Schmidt (Die Massenaustausch in freien Luft, H. Grand, Hamburg, 1925) has shown that the equation for this distribution is

$$CM + (\epsilon/\rho)(dm/dz) = 0 \tag{8}$$

Here, (ϵ/ρ) is a quantity having the dimensions of kinematic viscosity, but which has a value dependent upon the turbulent interchange. Christiansen has applied this formula with some success to measured velocity-distributions, but it has the disadvantage of giving only relative values of m, the percentage concentration. In order to use this formula to predict a silt-distribution curve, it is necessary to provide a means of predicting the absolute magnitude of the concentration of silt at a known distance from the bed.

Since suspension is merely a final stage in the transportation-phenomenon, existing concurrently with bed-transportation, the discussion of the factors affecting the latter is applicable to the determination of the concentration of sediment near the bottom. The local velocity-gradient should control the concentration, and the analysis of data in the field and laboratory should be based upon those related variables which are most readily available. From the standpoint of energy, T_0U_m or sq are satisfactory, but both involve s which is necessarily the average over a reach.

Conclusions--Experiments in the laboratory on the transportation of silt, especially on bed-movement, have not yielded results which can be used with confidence for estimating the transport of natural streams. Extensions of present methods to larger flumes and small natural channels promises to be equally inconclusive, although such work may yield approximate formulas.

To provide a satisfactory basis for computing the transport, it appears to be necessary to examine the phenomenon in detail, especially in the region immediately adjacent to the bed. This work will require improved sampling devices and instruments capable of indicating velocity-fluctuations and should be planned so as to utilize our present knowledge of turbulent flow.

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THE TWIN PROBLEM OF EROSION AND FLOOD-CONTROL

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In approaching this problem, a dual view must be taken of its two basic elements, soil and water. The essence of the problem with regard to each is the question of changes from geologic norms brought about by human agencies. The view must also take fully into account the reciprocal relations of these basic elements: First, in the upland headwater-regions of watersheds where waters and sediment gather to form silt-charged floods; and second, in trunk-valleys where floods spread and distribute their sediment-load.

Changes in water and sediment-output from upland areas

In headwater-gathering grounds of flood-waters and soil-debris, the typical effects of accelerated erosion are the removal of topsoil and subjacent horizons by sheet-erosion and the development of open channels in the form of gullies. In general, the changes in runoff from given precipitation brought about by these changes in terrain trend toward the ultimate, so-called "tin-roof-and-gutter" type of gather and flow, and, according to stage of development, give both greater volume and greater rapidity of inflow from divides and slopes into headwater-valleys. The increase in volume comes from reduced rates and time of infiltration of rainfall into bared and thinned topsoils, or into subsoils that have been exposed by erosion as new ground-surface. The increased rapidity of runoff comes from substitution of concentrated flow in channels with large hydraulic radius and with over-steepened gradients toward their heads for the relatively thin and generally distributed sheet-flow that originally characterized runoff from the same slopes prior to their modern erosional dissection. The power and capacity of surficial waters for picking up and carrying debris are correspondingly increased as a result of greater volumes and velocities of inflow into upland valleys.

The general change in outflow from upland areas are summarized in delivery of abnormally high, steep-fronted flood-waves carrying abnormal quantities and qualities of debris to the heads of major valleys. It is in such valleys, particularly those of alluvial character, that aggravated floods take their principil toll. In the valleys thus affected, the original channels, overbank-lands, gradients, and flood-flow levels were established in adjustment to lower primeval orders of water- and sediment-supply. Under the new conditions of water- and sediment-delivery, occasioned by accelerated erosion, their flood-flow levels are raised directly as a result of increased volumes of water and indirectly and progressively in keeping with aggradation of stream-channels and valley-lands. The rates and limits of aggradational readjustment of flood-levels relates to increase in either the quantity or the coarseness of grain of the new sediment-load, or both.

Viewed in detail, the readjustment of stream- and valley-features to increased debris-load present a multitude of different, intricately interrelated phenomena. Their combined effects on floods, however, may be summed up as in general terms of change in volume or configuration of topographic cavity. In a valley, or section of valley, there is a definite volume of cavity that flood-waters can occupy below the levels of any datum flood-flow line. By definition, in so far as aggradation is under way, this volume of available cavity is subject to progressive reduction measured in rate by the difference in volume, in settled condition, of incoming and outgoing debris-loads. A very simple basic equation may be useful to fix this fundamental fact, namely

$$(L - L') = D$$

in which L = load delivered into the valley-area from upstream, L' = load delivered out of the area downstream, and D = the volume of deposited debris.

In this equation of change in cavity-volume, stream-load does not refer to any particular solid matter, but only to the aggregate volume of debris in motion from place to place. Any particle of detritus while actually in motion under stream-agency is a part of the load and all such particles together comprise total load of the part of the river-system being considered, whether it be a single cross-section, a reach, an entire stream, or a river-system. An individual particle may be a part of load one instant and a part of the river-bed the next. It may thus alternate between load and river-bed with frequencies varying from a fraction of a second to untold years in interval. Load-characteristics therefore relate not to particular particles, but to volumes and kinds of matter in relation to space and time. Load is thus a measure of the exercise of stream-capacity for transportation of debris and in all cases is a margin of entrainment over detrainment by stream-agency in the whole drainage-system downstream from divides to points of measurement.

The concepts of limited volume of cavity below datum-levels in each valley-section and of volumetric rates of cavity-depletion by sediment-accumulation can be of great assistance to clear consideration of the longer time aspects of flood-level change and flood-control. This is particularly true with regard to flood-control practice on large aggrading rivers where datum-levels are fixed by maximum practical levee-grades. In such cases, the permission of continued aggradation at any rate spells inexorable advance toward eventual inadequacy of the waning remnant of original cavity safely to confine major floods, at least those of higher orders.

The applicability and portent of this principle is well illustrated in the alluvial valley of the lower Mississippi where present levee-grades are at or near the practical maximum height permitted by foundation-conditions. The total volume of cavity of the leveed trough through the valley below levee-grades is approximately 15 cubic miles. Sediment-observations of record on the Mississippi have been carried on through full but not identical full-year periods and for shorter periods of identical time. Fortunately, there is such a concordance between volumetric ratios of incoming and outgoing load relative to the general aggradational region of the valley, derived separately from the two different sets of data, that the trend and general magnitude of change in volume of cavity of the leveed trough appear to be well indicated.

The following summary of indicated incoming and outgoing loads for the region below Cairo, Illinois, is followed by reference to the sources of the data upon which it is based:

Yearly periods, not identical time	cubic yards	
Incoming load	447,000,000	(a)
Outgoing load	277,000,000	(b)
Accumulation	170,000,000	
Percentage of incoming load evacuated through the River's mouths	62	
Percentage of incoming load deposited in the alluvial region	38	
Part-year period, identical time (c)		
(69-day period from March 21 to May 28, 1929)		
Incoming load, Hickman, Kentucky	140,851,242	
Three per cent addition from Arkansas and Red rivers	4,225,537	
	145,076,779	
Outgoing load, Carrollton, Louisiana	95,305,974	
Accumulation	49,770,805	
Percentage of incoming load evacuated through the River's mouths	65	
Percentage of incoming load deposited in the alluvial region	35	

[References: (a) Report, Special Board of Engineers, 1909, House Document 50, 61st Congress, 1st session, p. 47; (b) Humphreys and Abbott, Report, 186, pp. 149-150; (c) official records of sediment-observations, Engineer Corps, 1929, M.R.C. files.]

Of the many other sets of data collected by investigations other than those cited above none is out of harmony with the indication that load entering the alluvial region of the Mississippi River exceeds outgoing load by about 170,000,000 cubic yards a year or by an amount of solid matter equal to a prism a mile square and 164 feet high. Such an average annual volume of material deposited would give an equivalent loss of cavity-space amounting to 0.2 per cent of the total per year or one per cent in five years.

At this rate, in the 200-year period since the first levees were built at New Orleans, about six cubic miles of detritus would have been added to the alluvial deposits of the area subjected to inundation below Cairo, an amount equal to 40 per cent of the aggregate channel, overbank, and backwater space now available to river-water occupancy without encroachment upon adopted standards of levee-freeboard.

The annual addition of 170,000,000 cubic yards of material to the 2385 square miles of combined channel and overbank-area between the levees from Cairo to Baton Rouge, if distributed evenly, would raise the ground-surface about 0.07 foot a year. But resurveys of channel cross-sections throughout the region below Cairo show a slight general increase rather than decrease in channel-space (70th Congress, 1st session, Comm. Doc. No. 1, p. 15). This implies that the volumes of material deposited in the valley went entirely to overbank-areas. If evenly distributed over the 1524 square miles of such territory, 170,000,000 cubic yards of accretion would lift the surface-level about 0.11 foot a year.

The foregoing analysis is based upon acceptance of the difference between Cairo and Carrollton loads at the rate of detritus-accumulation in the region between Cairo and Baton Rouge. The results of sediment-investigations of 1929, while not acceptable as conclusive proof regarding so important a matter, owing to the shortness of the period of simultaneous observations at successive points on the River, indicate strongly that greater difference in load may occur between Cairo and Old River than between Cairo and Carrollton, and that the average rate of accumulation in the overbank-areas in question may be higher than the figure of 0.11 foot per year as derived above. During the 69-day period of simultaneous observation in 1929 from March 21 to May 28 the following total-load volumes were derived for corresponding points along the River:

	cubic yards
Hickman, Kentucky	140,157,216
Lower Delta Point	89,558,200
Friar Point	74,175,000
Tarberts Landing	64,614,981
Red River Landing and Simmesport combined	63,172,536
Carrollton	95,305,974

What the proportionate relations of loads past these points may have been during the rest of the year is not shown, but if they were the same as those of the loads during the period of observation, only 45 per cent of the Hickman load reached Tarberts Landing, ignoring any contribution of detritus from the Arkansas and minor tributaries. On the basis of 441,000,000 cubic yards as a full yearly load passing Cairo and coming from the Arkansas a loss of 55 per cent to overbank would involve deposition of 242,000,000 cubic yards or an average thickness of deposit of about 0.16 foot per year.

Reduction of levee-freeboard due to loss of overbank-area

An annual increment of 170,000,000 cubic yards of material to overbank-lands between Cairo and Baton Rouge, a direct valley-distance of 530 miles, would entail an average loss of 1650 square feet of overbank-area. Consequent readjustments of flowage would involve a slight elevation of water-surface and shift of discharge from overbank to channel due to net loss of average water-depth and velocity in overbank and increase in depth and velocity in channel-areas. Taking all of these factors into account, in computations too lengthy to be presented here, it appears that a potential annual loss of levee-freeboard of about 0.033 foot a year would entail an evenly distributed increment of 170,000,000 cubic yards to overbank-lands yearly in the indicated length of valley.

Loss of levee-freeboard under successive alluvial increments, year by year, would naturally be cumulative. Even under the foregoing minimum rate the time must arrive when computed freeboard for given levee-grades and discharge would give zero, and thereafter minus quantities.

The actual deposition of sediment in the valley is, of course, not evenly distributed in depth over the whole overbank-area. Instead, it is known to be irregular and locally accentuated along the length of the River and to encroach upon overbank-area adjacent to the channel, where velocities are higher, more extensively than in places remote from the channel where overbank-waters are relatively stagnant. Moreover, the changes in channel-areas shown by successive range-surveys indicate important local encroachments of sediment upon channel as well as overbank-space. The effects of these factors would be to raise the rate of rise of flood-flow line of the River above the minimum computed for evenly distributed increments of sediment over the valley. The actual rates of rise in flow-line of the river, although never made the subject of special exhaustive investigation, are at least generally indicated by data on discharge-stage relations in the records of standard discharge-observations at various stations along the River. For a long period prior to 1927 in the region above Memphis these records indicate a gradual rise in flood-flow line at an average rate of about 0.3 foot a year. From 1929 to 1933, both at Hickman, Kentucky, and Friar's Point, Mississippi, a rise of three feet in four years, or 0.75 foot a year occurred. From 1933 to 1935, at the Hickman Station, a further rise of 1.5 feet in two years occurred, or again 0.75 foot per year, indicating persistence of this critical rate at this particular station over a total period of six years, and an aggregate rise of 4.5 feet.

Even the theoretical minimum rate of rise in flood-levels due to accretion of sediment in the valley would be sufficient to have frustrated the original unsupplemented levee-practice on the River in due time. The occurrence of actual rates of rise in flow-line higher than the theoretical minimum, due in part, at least, to localization of sediment-increments, justifies all the more the final abandonment of the old "levees-only" theory in the revised plan adopted in the Flood-Control Act of 1928.

Smaller streams than the Mississippi in many instances illustrate more advanced stages of alluvial readjustment of valley-features and flood-levels to accelerated erosion in tributary watersheds. Current studies in the basin of the Yazoo, tributary to the Mississippi at Vicksburg, reveals that aggradation in many places has completely filled the original channel and valley-cavity below datum-levels of maximum primeval floods. In these cases, the present-day accentuated flood-flows are carried through new flowage-area lying entirely above original flood-levels so there can be no question of the fact that flood-levels have been raised in catastrophic fashion as a consequence of recent man-induced upland erosion.

Many other streams in this and other parts of the Mississippi Watershed are to be found in various intermediate stages of morphologic and consequent flood-level readjustments.

In this connection it is important to emphasize the down-valley trends of progressive stream- and valley-adjustment to accelerated headwater-erosion. It is a general law of stream-function that tributaries force-feed trunk-channels with water and debris which they must receive, handle, segregate, store, and deliver. Earlier readjustments of tributary streams and valleys are toward improved capacities for delivery of abnormal flood- and sediment-discharges to trunk-valleys. The readjustments now broadly in effect on headwater-streams are on the march and are destined to extend indefinitely with time unless halted. The influence of our civilized activities through accelerated erosion, and conversely, the effects of erosion-control, thus have a direct and critical bearing upon our national problems of flood-control and navigation on even our largest rivers.

The laws of physical and morphologic sciences involved in the extended sequence of processes and effects of civilized land-use are exceedingly complex and as yet are only partially and imperfectly known. While it is certain that the primary effects of accelerated erosion can be controlled by now well-established means, much of practical importance remains to be learned of subsequent phenomena and possible additional practices beneficial to flood- and sediment-control.

These problems of our lands and waters are in a very true sense not separate and distinct, but are so linked by laws of sequence of the single natural phenomenon of land planation by water under the influence of man as to comprise a single general problem to be regarded even as twin only because our two greatest fundamental national resources are involved.

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EXPERIMENTAL STUDY OF THE SCOUR OF A SANDY RIVER-BED BY CLEAR AND BY MUDDY WATER

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(Abstract)

The purpose of this investigation was to determine the difference in the scour produced in a bed of fine sand by muddy water, as contrasted with clear water, in attempted simulation of the conditions existing in the Colorado River below the site of the Boulder Dam before and after construction.

A tilting-flume 40 feet long, 20 inches wide, and 18 inches high was used for the experiments. The sand-bed was eight feet long. Sand from the Colorado River was used, as well as local coarser sands. The suspended load of the River was simulated by Georgia kaolin, comparable in particle-size with the suspended load of the River.

The sand-bed was first settled under water, then water was allowed to flow over the bed under the desired conditions for one hour, no additional material being added upstream from the test-bed to replace the sand scoured and carried away. The amount of scoured material, the amount of clay in suspension, the conditions of flow, and the appearance of the bed were noted, and samples of the material scoured and the suspended load were analyzed.

It was found that when the water contained an appreciable amount of clay in suspension, an increase of about ten per cent in mean velocity over that of the clear water was required to produce the same amount of scour for the Colorado sand. For the coarser sands this increase was considerably greater. It was also shown that a very considerable increase in scour resulted from a small increase in mean velocity above that necessary to start scour. Values of critical tractive force and mean and bed-velocity were determined for "critical movement" when the sand-grains were just beginning to move in the form of riffles.

Table 1

Sand	Average diameter	Kaolin in suspension	Critical values		Higher values	
			Mean velocity	Tractive force	Bed-load scoured	Corresponding mean velocity
	microns	per cent	fps	lb/sq ft	lb/sq ft/hr	fps
Local sand	384	clear water	1.2	0.0088	1.5	1.23
	398	2.7	1.4	0.0125	1.5	1.53
Colorado	107	clear water	0.8	0.0077	0.6	0.90
	109	1.4	0.9	0.0087	0.6	0.98

Although the investigation in the laboratory can not be applied quantitatively to the Colorado River, it is concluded that there will be more scour and resulting transportation of the river-bed by clear water, if this is discharged from the dam, than was the case with muddy water.

[Note--It is expected that this paper will appear shortly in the Journal of Research, National Bureau of Standards, in much more complete form than the above abstract.]

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FLUVIAL MORPHOLOGY IN TERMS OF SLOPE, ABRASION, AND BED-LOAD

Samuel Shulits

Introduction

Fluvial morphology may be defined as the science of the forms of river-beds, their shapes in plan and in profile. There seems to be no satisfactory explanation of the cause of lateral migration of streams, that is, of the phenomenon of serpentining or meandering; and this is also true of the rhythm of change of the profile as seen in the downstream-progression of its pools and concomitant shoals. Extant knowledge is generally qualitative; if quantitative, it is usually of empiric origin and applicable only to a particular stream. Still there are some universal quantitative principles of fluvial morphology that have been developed theoretically. The purpose of this paper is to present, first, a very brief statement of some of the qualitative observations and, second, a more detailed statement of several quantitative laws and their use.

The morphological or bed-forming activity of a river is reflected to a considerable extent in its bed-slope. Meandering is a lengthening or shortening of the course and consequently a decrease or an increase of slope, respectively. Meandering usually occurs in the lower reaches where the bed-material is comparatively fine as a result of its travel and the bed-slope is small, thus suggesting a reciprocal relationship between size of material (or abrasion) and slope. That the slope adjusts itself immediately to changes in bed-load is too well known to need additional comment. Hence the principles of fluvial morphology are manifested in slope, abrasion, and bed-load.

Empiric observations

There is nothing final about the views expressed below; in fact, some of them are quite controversial. No attempt has been made to maintain a continuity of ideas. The numbers in brackets refer to the bibliography at the end of this paper and the page in the reference.

The cause of meandering or "tortuosity" of rivers is the existence of a slope exceeding that required to transport the fine material composing the bed-load. The river flattens its slope by lengthening its course, in other words, by meandering. Serpentining starts in a river, as a rule, at a bar that for some reason has formed at one bank and crowds the stream over to the other bank and so, back and forth [1, p. 143].

Where water is stored in reservoirs, the river flattens its slope downstream from the dam by degradation [2]. This is equivalent to shortening its true length, the horizontal projection remaining unchanged, of course.

The effect of diversion without storage on the river-bed below the intake depends on the given conditions. If a 50 per cent diversion is made from a straight stretch, more than 80 per cent of the bed-load enters the canal regardless of the angle of intake [3]. The lesser load in the main stream below the intake will cause a flattening of the slope or degradation down to the next control. In the case of draw-off from the outside of a bend, little or no bed-load enters the canal [4] and the overladen main stream will increase its slope (aggradation) so that the load can be transported. Almost nothing is known about the effect of bifurcation on the suspended load.

A cut-off results in degradation above the cut-off and aggradation below. This will be treated quantitatively below.

Dams or weirs in a river act as controls, their crests being the ultimate elevation the bed will attain. This is also true of ground-sills or rock-ledges in the bed [2].

Reduction of the bed-load induces a decrease of slope (degradation, meandering or longer meanders) and vice versa [2].

The river-width increases downstream. Investigation of several hundred cross-sections led Schoklitsch [1, p. 145] to conclude that the width increases along the stream in direct proportion to the six-tenths power of the yearly runoff (or the drainage-area for approximations).

Rational morphologic laws

Sternberg abrasion-law--As the particles of bed-load move downstream, their size is reduced by abrasion, collision, and solution [5, 6]. The most important of these is abrasion, for which Sternberg developed a theoretical law that has been verified experimentally by Schoklitsch [5, 6, 7]. Sternberg assumed the reduction in weight of a particle to be directly proportional to the work done in overcoming friction in the distance traveled [8, p. 483]. Let P be the weight, φ the coefficient of friction, and x the distance traveled (measured positive downstream). If c is a constant of proportionality, then the decrease in weight caused by abrasion in the distance x is

$$dP = -c(\varphi P dx) \quad (1)$$

or

$$dP/P = -c\ \varphi\ dx \quad (1a)$$

Integration yields

$$\log_n P = -c\ \varphi\ x + C \quad (2)$$

When $x = 0$, $P = P_0$, and $C = \log_n P_0$. Finally

$$P = P_0 e^{-c\ \varphi\ x} \quad (3)$$

which is the Sternberg abrasion-law. It is equally rational to assume that the abrasion is proportional to the weight of the particle and the distance traveled. This results in

$$P = P_0 e^{-ax} \quad (4)$$

in which $a = c\ \varphi$. It has become usual to use the coefficient "a" rather than the equivalent product $c\ \varphi$. From the differential equation (1), it will be seen that "a", the so-called coefficient of abrasion, is the decrease in weight suffered by a stone weighing one unit (of weight) in traveling one unit of distance and has the dimension, length^{-1}.

Values of the coefficient of abrasion for various rocks will be found in [5], [6], and [7]. Unfortunately, "a" is not a constant for a given rock. It increases with the one-fourth power of the velocity of the particle and is proportional to the diameter of the underlying material [5, p. 351]. The coefficient also depends on the shape of the pebble.

River-slope equation--Since the slope of a river decreases from source to mouth as the bed-load material (geschiebe) does, it seems logical to search for a relationship between slope and size of geschiebe. Consideration of a number of river-profiles showed the slope to be directly proportional to the particle-size [1, p. 147]. Mathematically expressed

$$S = \sigma P_0 e^{-ax} \tag{5}$$

where S is the slope (bed or energy-gradient) and σ a constant. Where $x = 0$, $S = S_0$, so that $\sigma P_0 = S_0$ and

$$S = S_0 e^{-ax} \tag{6}$$

which is the equation of the slope of the river. The author found that this equation fitted the profile of the Colorado River between Boulder Dam and the Arizona-Sonora Boundary approximately.

Let z be the elevation of any point on the profile above a given datum. Then

$$S = (dz/dx) = S_0 e^{-ax} \tag{7}$$

$$dz = S_0 e^{-ax}\, dx \tag{8}$$

Integration yields

$$z = (S_0/a)\, e^{-ax} + C \tag{9}$$

where $x = 0$, $z = z_0$, and $C = z_0 - (S_0/a)$, so that finally

$$(z_0 - z) = (S_0/a)\,(1 - e^{-ax}) \tag{10}$$

The profiles of the Middle Rhine (Mittelrhein), the Maas, the Mur, and the Enns rivers in Europe conform to this equation [1, p. 147].

Sternberg arrives at a river-slope equation by a more devious route [9, p. 533]. Combination of his abrasion-law (3) and the theoretical fact that the mean velocity just capable of moving a particle is proportional to the one-sixth power of its weight yields a relationship between mean velocity, size of grain, and distance traveled by the grain. Substitution of the Chézy formula into this relationship after the rather arbitrary assumption that the river-width increases downstream directly as the discharge, results in

$$(z_0 - z) = 2(S_0/a)\,(1 - e^{-ax/2}) \tag{11}$$

It is also claimed [9, p. 534] that this equation fits the slopes of the rivers mentioned above under equation (10).

Putzinger [10] assumes the reduction in particle-size to be proportional to the work done by the tractive force in the distance traveled. His slope-equation is of the same general form as (10) and (11), namely

$$(z_0 - z) = k_1(1 - e^{-kx}) \tag{12}$$

where k_1 and k are constants.

It can therefore be concluded with reasonable certainty that the slope of a river follows the general law expressed by equation (12). It is the domain of research to clarify the significance of the constants and ascertain their values.

Bed-load and abrasion--As the bed-load moves downstream, it is conceivable that at some point in the stream the runoff may be insufficient to move the load and vice versa. The abrasion-law gives some clues in this matter.

The Schoklitsch bed-load formula is

$$G = [86.7/\sqrt{d}]\,[S^{1.5}\,(Q - Bq_0)] \tag{13}$$

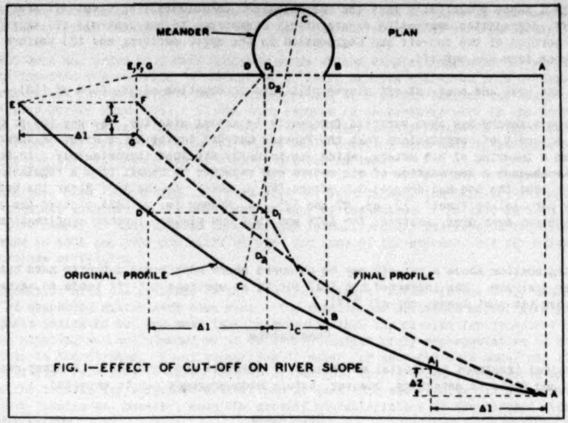

FIG. 1—EFFECT OF CUT-OFF ON RIVER SLOPE

in which G is the bed-load in lb/sec, d is the grain-diameter in inch, S is the energy-gradient, Q is the instantaneous discharge in cusecs, B is the width in ft, and q_0 is the critical discharge at which the material just begins to move in cusecs per ft [11]. The value of the latter is

$$q_0 = 0.00532/S^{4/3} \tag{14}$$

From $P = P_0 e^{-ax}$ it follows that

$$d = d_0 e^{-ax/3} \tag{15}$$

Substitution of the above and $S = S_0 e^{-ax}$ into the Schoklitsch bed-load formula yields finally

$$G = KQ/e^{(4/3)ax} - K_1 B/e^{ax/3} \tag{16}$$

If the discharge- and width-terms increase equally downstream, there is no change in bed-load. However, if the Q-term increases more rapidly than the other term, there will be an increase in bed-load and a change in profile, probably degradation and an increase in slope. Should the B-term increase more rapidly, there would be a decrease in load and a corresponding change in regimen. Equation (16) can be used to show the interrelation between bed-load, drainage-area, runoff, and abrasion along the course of the river. It may also explain breaks in the profile.

Analytical treatment of effect of cut-off--Figure 1 presents diagrammatically the plan and profile of a river with a meander in it. The river in its original condition is represented by line AA_1BCDE, the meander being BCD. It is assumed that the slope is continuous and regular through the meander. The point A is a control where the bed-elevation is maintained constant.

The meander is eliminated completely by cutting a channel from D to B. At the instant of cut-off the river is as shown by line AA_1BD_1F, a straight-line slope being assumed in the cut-off. The length of the cut-off is l_c and the shortening is Δl.

The effect of the shortening is to decrease the distance traveled by the particles. Hence coarser material will arrive at the control A and a steeper slope must develop there to transport it. The slope at A will be that which existed originally at A_1, which is a distance Δl upstream from A. The final slope of the river from A upstream will be the same as that between A_1 and E on the old river. The new slope will be AD_2G and is constructed by moving the line A_1E downstream horizontally a distance, Δl, and dropping it vertically a distance, Δz, the height of A_1 above A. The final slope, D_2G, above the cut-off is parallel to DE or D_1F of the original profile. The difference in elevation between D_1F and D_2G is Δz, the amount of degradation above the cut-off.

Figure 1 shows graphically that the morphological consequences of a cut-off are: (1) Below the cut-off, aggradation decreasing progressively downstream to the control; (2) aggradation in the lower portion of the cut-off and degradation in the upper portion; and (3) uniform degradation upstream from the cut-off.

Both the pre- and post-cut-off slopes will have an equation of the form of (12).

The above theory has been verified frequently in actual practice. S. Wey [9, p. 543] predicted as a result of computations that the Fussach Cut-Off in the Rhine River in Vorarlberg would cause a lowering of 2.4 meters, which was actually attained approximately. In the Lech River at Lechhausen a degradation of six meters was expected to result from a regulation begun in 1852; by 1884 the bed had dropped 5.2 meters [9, p. 543]. In the Aare River the bed dropped 3.0 meters parallel to itself [12, pp. 27 and 69]. A. Brunar [9, p. 543] plotted the profiles of the Mur River near Graz, Austria, for 1876 and 1904 and yielded further confirmation of this theory.

The degradation above a cut-off may be obscured where additional cut-offs have been carried out farther upstream. The increased bed-load due to an upstream cut-off tends to aggrade the stretch above the next lowest cut-off [13].

Conclusions

Analytical treatment of fluvial morphology is possible and practical. Further research in laboratory and field is necessary, however, before much progress can be expected.

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UNITED STATES GEOLOGICAL SURVEY RECORDS OF SUSPENDED AND DISSOLVED MATTER IN SURFACE-WATERS

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Although the widest-known and most conspicuous task of the United States Geological Survey with reference to surface-waters has been the measurement of discharge, attention has always been given to the suspended and dissolved matter carried in them. From 1902 to 1909 the Survey published about 20 reports on the quality of surface-waters. These reports dealt largely with stream-pollution and its prevention, subjects that have not been included in the work of the Geological Survey since the Public Health Service began investigations of them in 1913

In 1905 work was begun on a comprehensive study of the chemical character of surface-waters. The project involved the analysis of composites of daily samples collected from streams in different parts of the United States. One report included 71 stations east of the one-hundredth meridian (Water-Supply Paper 236). Others were reports on cooperative work in the States of California, Illinois, Kansas, Washington, and Oregon (Water-Supply Papers 237, 239, 273, 339, 363). The report for Oregon (Water-Supply Paper 363), covering work done in 1912 and published in 1914, was the last of the series of reports started in 1905.

The analyses made between 1905 and 1912 give the best information that is available today as to the chemical composition of the waters of many of the streams. In 1930 partial analyses were made of a number of spot-samples from streams in California. The results indicate that the analyses made in 1906 and 1908 may still be used for some of the streams, but for others the old analyses are now misleading.

In connection with the analyses of the dissolved mineral matter in the early studies, determinations of suspended matter were also made. The results for suspended matter were published in the reports indicated but are much less trustworthy than the results for dissolved matter. Much of the sampling was not planned so as to obtain samples truly representative of the suspended matter in the streams. Equal quantities of water for each day were made into 10-day composites without reference to variations in discharge. This procedure introduces much more error into the results for suspended matter than it does into the results for dissolved matter. The published results do, however, show the general characteristics of the streams with respect to suspended matter.

In addition to the systematic reports in the series just described, the Geological Survey has issued as Water-Supply Paper 274 a report of a large number of analyses and tests made by the United States Reclamation Service from 1905 to 1907. The report contains no complete analyses like those in the other surface-water reports but gives many determinations of certain constituents in daily samples, partial analyses of weekly composites, and partial analyses of monthly composites. Suspended matter is also reported. The samples were taken from rivers that were under consideration by the Reclamation Service as sources of water for irrigation-projects.

The series of reports on the composition of surface-waters did not cover the country adequately or uniformly. The report for the area east of the one-hundredth meridian (Water-Supply Paper 236) included one station for about 15,000 square miles of area. The State reports (Water-Supply Papers 237, 239, 273, 339, and 363) had one station for 2000 to 4500 square miles of area.

In 1929 work was begun on a two-years' study of the composition of the surface-waters of Virginia in cooperation with the State Commission on Conservation and Development. The report of this work, which was published by the State, gives analyses of composites of daily samples collected for one year at 33 gaging-stations. Analyses are also given of spot-samples collected at high and low stages at 70 other stations. The analyses are more complete than those made in the earlier Geological Survey studies of the composition of surface-waters and are accompanied by records of discharge.

In 1925 work was started on measuring the suspended and dissolved matter in the water of the Colorado River. Samples have been taken for different periods at 11 gaging-stations in Arizona, Utah, and Colorado. Intensive studies of silt-movement have been made on the San Juan River, on the Little Colorado, and on the Colorado at Grand Canyon. These studies involved work at the gaging-stations for periods of several months during floods in summer. Results from the 10-year studies of suspended and dissolved matter will be presented in papers that follow. (Published results are contained in Water-Supply Papers 596-B, 636-A, 638-B, and 638-D.)

In connection with the operation of eight regional projects of the Soil Conservation Service, it was desired to obtain records of the quantities of water and suspended matter carried out of the drainage-basins in which erosion-control work was to be done and the quantities carried out of similar drainage-basins on which the control-methods were not used. An allocation of Public Works funds was made to the United States Geological Survey in January 1934 primarily for the establishment and operation of stream-flow-measurement stations and for obtaining records of movement of suspended matter at eight erosion-control projects.

The work on these Soil Conservation Service projects has called for somewhat more detailed measurements of stream-flow and more comprehensive sampling programs than has been found necessary for other projects involving the measurement of movement of suspended matter. This is a consequence of the rapidly and irregularly changing concentration of suspended matter with changing discharge, of which instances will be given in one of the papers that follow. In a period of about 15 months, 56,600 pint samples were collected from streams at 34 gaging-stations, and the quantity of suspended matter in each sample was determined. Only a few spot-samples for analysis of the dissolved matter have been taken from the streams in and near the Soil Conservation projects.

The three papers that follow are based on records of suspended and dissolved matter obtained in studies of the Colorado River and of streams in and near eight Soil Conservation Service projects.

The records of suspended and dissolved matter in the Colorado River Basin and the records of suspended matter at 34 stations on streams in and near the Soil Conservation projects, together with records of dissolved matter at 33 gaging-stations in Virginia, include all the recent comprehensive work of this character done at any of the nearly 3000 gaging-stations at which discharge-records are being obtained. There would probably be no justification for making at every gaging-station such intensive studies of the suspended and dissolved matter as are being made at the stations for which records will be presented in the papers that follow. There is, however, no doubt that much wasteful and inadequate planning of public or private work would be avoided if comprehensive records of suspended and dissolved matter were available for many more river-stations.

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SUSPENDED MATTER IN THE COLORADO RIVER, 1925-1935

C. S. Howard

(Published with the approval of the Director, U. S. Geological Survey)

The rugged topography of a great part of the Colorado River Basin is a significant factor in determining the quantity of water and suspended matter carried by the River. The mountainous regions of Colorado and Wyoming contribute a large part of the flow of the River, whereas the central part of the Basin, cut by deep gorges and canyons, contributes a large part of the suspended matter carried by the River.

The discharge of the Colorado River as measured near Cisco, Utah, with a drainage-area of 24,100 square miles is slightly greater than the discharge of the largest tributary, the Green River, measured near Greenriver, Utah, with a drainage-area of 40,600 square miles. The Green, however, carries a considerably larger load of suspended matter. Two other tributaries, the San Juan and Little Colorado rivers, each with a drainage-area of about 25,000 square miles, carry large loads of suspended matter in proportion to their discharge. For example, the Little Colorado River in the summer of 1931 contributed less than 10 per cent of the flow of the main river at Grand Canyon, but the Little Colorado carried about 10,000,000 tons of suspended matter during this period and the main river had about 25,000,000 tons for the same period.

Suspended matter in the Colorado River, as in other turbid rivers, varies considerably from period to period, but there is no direct relation between the load of suspended matter and the discharge of the River. The load of suspended matter in the Colorado River shows the greatest variation and the largest daily loads in summer during floods caused by rains of high intensity in the desert country. The sum of the loads for a few days during these floods may comprise 30 to 40 per cent of the annual load. The loads carried at two widely separated stations on the River may show large differences for any short period of time, indicating deposition at certain times and scouring of the channel at other times. These differences are less apparent over long periods, and for a period of nine years the total load carried past the Topock gaging-station in the lower river was about equal to the load carried past the Grand Canyon gaging-station nearly 400 miles upstream.

The nature of the suspended matter shows considerable variation over a period of a year, particularly in the sizes of the particles of the material carried. The suspended matter carried during the spring floods consists largely of particles having diameters greater than 20 microns with a considerable proportion of the particles greater than 50 microns. The suspended matter carried during the summer floods, and at other times when the greater part of the material comes from the desert country, consists chiefly of particles with diameters less than 20 microns.

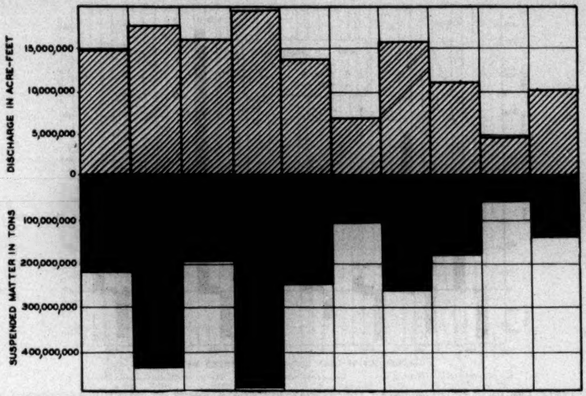

FIG. 1—DISCHARGE AND SUSPENDED MATTER FOR COLORADO RIVER AT GRAND-CANYON GAGING-STATION

The material along the banks and in the bed of the River in deposits from Grand Canyon to Yuma consists chiefly of medium and coarse sand, individual particles having diameters greater than 50 microns, indicating that the finer particles usually are carried in suspension down the River. This deposited material, consisting of only certain sizes of material, weighs about 85 pounds per cubic foot and this weight has been used in the computation of the volume of reservoir-deposits. The greater part of the suspended matter carried past Grand Canyon has been deposited in Lake Mead since February 1, 1935, when Boulder Dam was closed for the storage of water in the Lake. The estimated volume of the material deposited in the Lake from February 1 to September 20, 1935, was about 55,000 acre-feet. During the same period the River below the Dam was scouring its channel, and in the 116 miles between the Dam and the Topock gaging-station about 8000 acre-feet (15,000,000 tons) was scoured out and carried past the Topock station.

The annual loads of suspended matter at the Grand Canyon gaging-station for a 10-year period are shown in Figure 1 with the discharge for the same years. The annual loads during this period show variations from about 50,000,000 tons to nearly 500,000,000 tons, which are greater than the variations in annual discharge for the same years. The year of lowest flow, 1933-34 (about 5,000,000 acre-feet), was also the year of lowest load of suspended matter. The year of highest flow, 1928-29 (about 19,000,000 acre-feet), also had the largest annual load of suspended matter. The load for this year (nearly 500,000,000 tons) was the largest annual load that has been reported for the Colorado River. The average annual load of suspended matter, based on the results of this 10-year study by the Geological Survey, is about 250,000,000 tons, which on the basis of a weight of 85 pounds per cubic foot of deposited material would occupy about 140,000 acre-feet of storage space in a reservoir.

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Washington, D. C.

SUSPENDED MATTER IN SEVERAL SMALL STREAMS

S. K. Love

(Published with the approval of the Director, U. S. Geological Survey)

The measurement of the loads of suspended matter carried past 34 gaging-stations located on streams in eight regional projects of the Soil Conservation Service has required greater precision in the measurement of discharge and a more intensive program for the collection of samples of suspended matter than has been found necessary by the Geological Survey in making similar measurements on the larger streams on which measurements have been made in the past. It was found early in the work that much the greater part of the annual load of suspended matter was carried

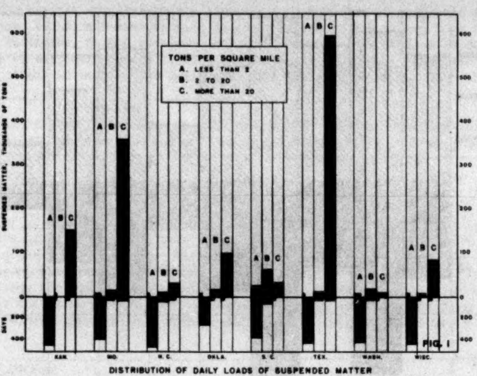


FIG. 1

DISTRIBUTION OF DAILY LOADS OF SUSPENDED MATTER

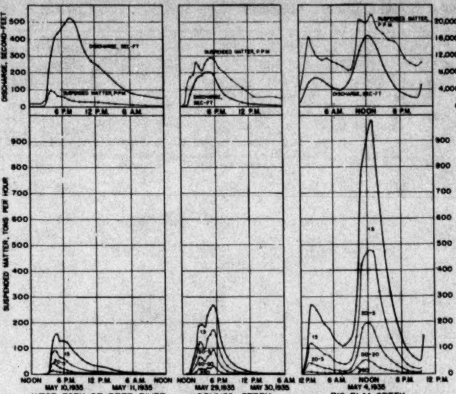
in a relatively few days of high water for almost all the streams on which measurements were made. In order that these loads might be determined with reasonable accuracy it was found necessary to collect samples every hour and occasionally every half-hour on rising and rapidly changing stages during floods. Some floods occurring at night were missed in part or entirely because the resident observer did not realize that a flood was in progress. Twenty-four-hour sampling programs, together with the aid of electric-alarm systems at some stations, have made possible the collection of an adequate number of samples during most floods.

The distribution of total loads of suspended matter into groups corresponding to different magnitudes for a typical stream selected from each of the eight Soil Conservation Service regional projects is shown in Figure 1. The black areas above the zero base-line represent the loads of suspended matter carried by each stream and the shaded areas below the zero base-line represent the number of days in which these loads were carried. Column A in the graph for each stream shows the number of days in which the movement of suspended matter was less than two tons per square mile, column B shows the number of days in which it was between two and 20 tons per square mile, and column C shows the number of days in which the quantity carried was more than 20 tons per square mile.

In South Carolina and Washington greater loads of suspended matter were carried by the streams at rates of from two to 20 tons per square mile per day, as shown in column B, than at lower or higher rates as shown in columns A and C. For all the other areas the greatest movement of suspended matter was at rates of more than 20 tons per square mile per day. It is readily seen that in almost every area the greater part of the total load of suspended matter was removed from the drainage-area in a very few days out of a total of about 450 days of record. In the area drained by Coon Creek at Coon Valley, Wisconsin,90 per cent of the total load was carried in 10 days, and in the area drained by West Tarkio Creek near Westboro, Missouri, 90 per cent of the total load was carried in 12 days.

A summary of the loads of suspended matter carried past each station, including the maximum load per square mile for a single day and for the 15-month period and some of the corresponding discharges, is given in Table 1. It is interesting to note that the total load per square mile of drainage-area carried in 15 months ranged from a minimum of 206 tons for Paradise Creek near Pullman, Washington, to 8948 tons for Big Elm Creek near Temple, Texas. It should be stated that the rainfall and consequently the runoff on the Washington project was relatively small during the period under discussion. Larger runoff and consequently larger loads of suspended matter may reasonably be expected during other periods of similar length. The maximum load per square mile in a single day, measured in Elm Creek near Ionia, Kansas, amounted to 1910 tons.

In order to learn something about the distribution of sizes of the particles carried in suspension, mechanical analyses have been made of a few series of samples collected during flood-periods on several streams. In Figure 2 are shown the results of mechanical analyses of samples of suspended matter collected during floods on the West Fork of Deep River near High Point, North Carolina, Council Creek near Stillwater, Oklahoma, and Big Elm Creek near Temple, Texas.



WEST FORK OF DEEP RIVER,
HIGH POINT, N.C.

COUNCIL CREEK,
STILLWATER, OKLAHOMA

BIG ELM CREEK,
TEMPLE, TEXAS

FIG. 2—DISTRIBUTION OF SUSPENDED LOADS OF DIFFERENT PARTICLE-SIZES

Table 1--Discharge and suspended matter in streams for 15-month period ending June 30, 1935

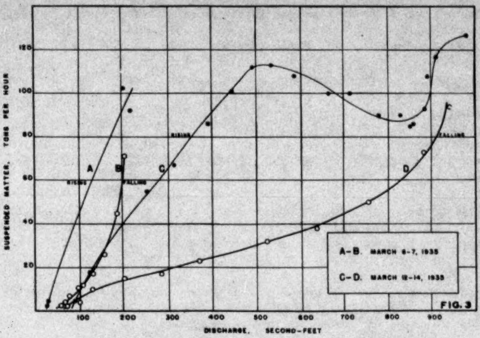
State and stream	Drainage-area	Discharge (a)=day max. suspended matter (b)=day max. discharge	Daily load suspended matter	Total load suspended matter for period	Maximum mean daily discharge per square mile	Maximum daily load suspended matter per square mile	Total load suspended matter per square mile
	sq mi	sec-ft	tons	tons	sec-ft	tons	tons
Kansas							
East Limestone Creek near Ionia	23.7	(a) 916	41700	179369	..	1760	7568
		(b) 1220	37000	....	51	...	...
Elm Creek near Ionia	23.2	(a,b) 1320	44200	154033	57	1910	6639
East Limestone Creek at Ionia	51.6	(a,b) 2940	83200	297452	57	1610	5765
West Buffalo Creek near Jewell	15.3	(a) 456	28000	118189	..	1830	7725
		(b) 615	17800	....	40	...	...
West Buffalo Creek at Jewell	16.3	(a) 468	20600	87503	..	1260	5368
		(b) 819	16900	....	50	...	...
Missouri							
East Tarkio Creek at Blanchard	200	(a,b) 655	42000	248098	3.3	210	1240
West Tarkio Creek near Westboro	127	(a,b) 666	54500	245141	5.2	429	1930
East Fork of Big Creek near Bethany	95	(a) 1090	29800	379511	..	314	3995
		(b) 1940	22000	....	20	...	...
North Carolina							
West Fork of Deep River near High Point	33	(a,b) 696	7910	43135	21	240	1307
East Fork of Deep River near High Point	13.9	(a) 133	2800	21238	..	187	1528
		(b) 289	447	....	21	...	...
Deep River near Randleman	124	(a) 1420	4990	76213	..	40	615
		(b) 2560	4780	....	21	...	...
Muddy Creek near Archdale	14.2	(a,b) 353	564	7535	25	40	531
Uharie River near Trinity	11.3	(a) 85	2680	18710	..	237	1656
		(b) 209	1370	....	18	...	...
Horsepen Creek at Battleground	15.9	(a) 286	965	11045	..	61	695
		(b) 287	533	....	18	...	...

Table 1--Discharge and suspended matter in streams for 15-month period ending June 30, 1935--Concluded

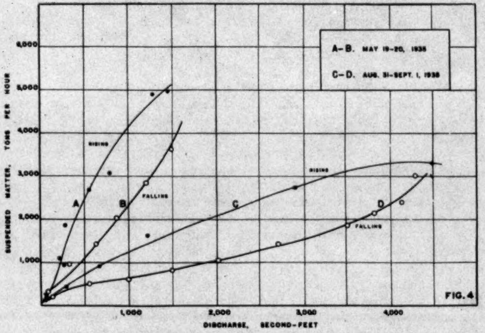
State and stream	Drainage-area	Discharge (a)=day max. suspended matter (b)=day max. discharge	Daily load suspended matter	Total load suspended matter for period	Maximum mean daily discharge per square mile	Maximum daily load suspended matter per square mile	Total load suspended matter per square mile
	sq mi	sec-ft	tons	tons	sec-ft	tons	tons
Oklahoma							
Stillwater Creek at Stillwater	165	(a,b) 7880	61800	118396	48	375	718
West Fork of Brush Creek near Stillwater	13.1	(a,b) 728	5610	15301	56	428	1168
Council Creek near Stillwater	30.2	(a,b) 604	10400	68781	20	344	2278
South Carolina							
North Tiger River near Moore	162	(a,b) 1170	3860	87453	7.2	24	540
South Tiger River near Reidville	106	(a) 641	3710	44320	..	35	418
		(b) 827	1720	....	7.8	...	...
South Tiger River near Woodruff	174	(a,b) 1150	6650	121501	6.6	38	698
Tiger River near Woodruff	351	(a) 1830	13800	349061	..	39	994
		(b) 3280	9450	....	6.9	...	...
Texas							
Deer Creek at Chilton	81.8	(a,b) 3910	127000	492986	48	1550	6027
Big Elm Creek near Temple	68.5	(a) 3220	102000	612958	..	1490	8948
		(b) 4330	89600	....	63	...	...
Big Elm Creek near Buckholts	166	(a) 4050	94100	655816	..	567	3951
		(b) 6020	47700	....	36	...	...
North Elm Creek near Ben Arnold	30.3	(a,b) 1160	22800	78385	38	752	2587
Washington							
South Fork of Palouse River above Paradise Creek near Pullman	81.1	(a) 242	2210	19624	..	27	242
		(b) 292	1700	....	3.6	...	...
South Fork of Palouse River at Pullman	132	(a) 424	3580	33216	..	27	252
		(b) 568	2650	....	4.3	...	...
Paradise Creek near Pullman	37.0	(a) 134	789	7632	..	21	206
		(b) 151	522	....	4.1	...	...
Dry Fork of South Fork of Palouse River at Pullman	7.42	(a) 23	430	1978	..	58	267
		(b) 44	154	....	5.9	...	...
Missouri Flat Creek at Pullman	27.5	(a,b) 164	1500	10014	6.0	55	364
Fourmile Creek at Shawnee	73.1	(a,b) 502	4600	28962	6.9	63	396
Wisconsin							
Little La Crosse River near Leon	77.1	(a) 298	13500	91901	..	175	1192
		(b) 884	7720	....	11	...	...
Coon Creek at Coon Valley	77.2	(a,b) 425	35000	97200	5.5	453	1259
Coon Creek near Stoddard	119	(a,b) 428	17600	105171	3.6	148	884

In the lower diagrams loads of suspended matter in tons per hour computed from samples collected at intervals of about one hour are plotted against time in hours for each of four ranges of particle-sizes. In the upper diagrams discharge in second-feet and concentration of suspended matter in parts per million are plotted against time in hours. The time-scale is the same in both upper and lower diagrams.

The curves in the lower diagrams are plotted cumulatively. The area under the bottom curve represents in tons the load of suspended matter consisting of particles greater than 50 microns in diameter. The area between the base-line and the second curve represents the load consisting of particles greater than 20 microns in diameter. Thus the area between the lowest two curves



WEST FORK OF DEEP RIVER NEAR HIGH POINT, N. C.



ELM CREEK NEAR IONIA, KANSAS

FIGS. 3 AND 4—RELATION BETWEEN DISCHARGE AND SUSPENDED MATTER

represents the load consisting of particles between 20 and 50 microns in diameter. The loads of the other sizes are plotted similarly so that the highest curve represents the total load in tons per hour.

Sudden changes in discharge are likely to be accompanied by corresponding changes in the loads of suspended matter. For the floods represented in Figure 2 the greater parts of the total loads and also the greatest changes in magnitude of the loads occur in the material whose particle sizes are less than five microns in diameter. Fifty-seven per cent of the total load carried in the North Carolina stream, 42 per cent of the total load carried in the Oklahoma stream, and 53 per cent of the total load carried in the Texas stream consisted of material less than five microns in diameter. The loads of relatively coarse material, that is, material greater than 50 microns in diameter, made up only 6.5 per cent, 8.5 per cent, and 4.2 per cent, respectively, of the total loads carried during the same floods.

Probably almost every investigator who has made a study of suspended matter carried by streams has considered the possibility of finding a definite relation between discharge and load of suspended matter.

Humphreys and Abbot [see 4 under "References" at end of paper] in their "Report on the Mississippi River" concluded from their studies on the Mississippi that no such relation existed. They stated that their studies revealed no relation between velocity of the stream and the load of suspended matter. They maintained that the Mississippi was never saturated with suspended matter.

Gras [3] assumed the power of a stream to transport solid material to vary "directly with the velocity, density, and depth of the water, and, these quantities remaining constant, to vary with the volume, density, and form of the solids submitted to its action."

Gilbert [2] reasoned that because fine particles sink more slowly than coarse particles, the same expenditure of energy by the stream will transport a greater load of fine particles than of coarse particles of the same density.

Cory [1], in connection with his work on the Colorado River, stated that "the Colorado at all times carries considerable silt, the quantity and character, of course, depending on the velocity of the water."

In their work on the Missouri River in 1929-32, the United States Army Engineers [5] developed rating curves for relations between discharge and suspended matter. The curve developed for determining the suspended load of the Missouri River at Kansas City is said to hold fairly well for discharges of less than 190,000 second-feet.

Data obtained from measurements of suspended matter and stream-flows on the Soil Conservation Service regional projects indicate that there may exist a fairly definite relation between discharge and suspended load at any time, but unfortunately this relation is apparently different for each flood. In Figure 3 are plotted curves representing the relation between suspended matter and discharge for two floods on Elm Creek near Ionia, Kansas. Curves A and B are for the flood of May 19-20, 1935, and curves C and D are for the flood of August 31-September 1, 1935. It is readily seen that a discharge of 1000 second-feet may correspond to a suspended load of 600, 1250, 2300, or 4000 tons, depending on the curve selected.

Figure 4 shows a similar pair of curves during two floods that occurred on the West Fork of Deep River near High Point, North Carolina. For a discharge of 200 second-feet a suspended load of 15, 40, 60, or 90 tons per hour might be selected, depending on which curve is used. Similarly, a suspended load of 100 tons per hour can correspond to a discharge of 470, 760, or 900 second-feet. This curve is particularly discouraging in attempting to develop a rating curve for discharge and suspended load, because the last three values are all read from a single rising-stage curve. It is probable that the influence of the factors affecting the energy of the water available for transporting solid material can be determined. It may also be possible, by making mechanical analyses of a large number of samples of suspended matter, to determine somewhat approximately an average distribution of the sizes of particles usually carried by a stream at different seasons of the year. It seems impossible, however, to predict even approximately the quantities of material that will be washed into the stream within a given period of time as the result of erosion of the drainage-area. The intensity and duration of rainfall are so variable as almost certainly to preclude any estimate of the amount of material that will be delivered to the stream. Up to the present time, there appears to be no easy way to estimate or compute with even approximate reliability the suspended load carried by any small stream except on the basis of careful frequent sampling during floods.

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U. S. Geological Survey,
Washington, D. C.

DISSOLVED MINERAL MATTER IN SURFACE-WATERS

W. D. Collins

(Published with the approval of the Director, U. S. Geological Survey)

The only unpublished comprehensive Geological Survey records of dissolved matter in surface-waters are the results obtained in the study of the Colorado River and its tributaries since 1930. The records are mainly analyses of 10-day composites of daily samples, although there are several analyses of spot-samples from some streams in the basin and about 4000 single determinations of chloride or sulphate in daily samples.

The need for a large number of analyses is shown by the fact that during the period 1925-35 the quantity of dissolved solids in 10-day composites from the Colorado River at Grand Canyon ranged from 226 parts per million for June 11-20, 1929, to 1889 parts per million for September 21-30, 1934. A series of analyses covering a whole year might be misleading. The weighted averages for the different years ranged from 491 parts per million for the year ending September 30, 1928, to 960 for the year ending September 30, 1934.

Comparative analyses made for different periods before the closing of Boulder Dam indicate that in general the content of dissolved mineral matter was practically the same at Grand Canyon, Willow Beach, Topock, and Yuma, Arizona. After the closing of the Dam in February 1935 the water in the River at Willow Beach, 10 miles below the Dam, began to show the effects of mixing in Lake Mead. The composite sample for February 1-10, 1935, at Willow Beach had 1214 parts per million of dissolved solids, which was practically the same concentration as at Grand Canyon. The dissolved solids at Grand Canyon decreased to 242 parts per million by June 21-30, 1935, whereas at Willow Beach the concentration of dissolved solids decreased only to 371 parts per million. The minimum concentration at Willow Beach was 276 parts per million for August 21-31, 1935, when the concentration at Grand Canyon was 1028 parts per million. More recently the analyses have seemed to indicate that mixing in Lake Mead is not complete, and as yet it has not been found possible to predict the probable composition of the water drawn from the reservoir on the basis of past records of the composition and the quantities of water entering and leaving the reservoir. Evaporation and the contributions of water between Grand Canyon and the Dam can not account for all the departures from the calculated composition. Assuming complete mixing and neglecting evaporation and inflow below Grand Canyon, the computed composition of the water in the Lake for February 1-10, 1936, shows a content of 570 parts per million of dissolved solids. The water flowing from the Lake during that 10-day period had 897 parts per million of total dissolved solids. The water at Grand Canyon at the same time had 1090 parts per million of dissolved solids.

From the analyses made up to this time it seems impossible to predict the composition of the water that will be let down from the reservoir in the future. The content of dissolved mineral matter can hardly ever be as low as in the waters of the spring-floods at Grand Canyon nor as high as in the more concentrated waters of the summer-flow.

U. S. Geological Survey,
Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

Pacific Coast Meeting, 1936

SECTION OF HYDROLOGY

Pasadena, California
January 31 and February 1, 1936

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SYMPOSIUM ON CONTRIBUTION TO GROUND-WATER SUPPLIES

GENERAL REVIEW

Harry F. Blaney

Introduction

Ground-water as a source of supply for domestic, industrial, and agricultural purposes is of prime importance in many sections of the United States and will continue to be a greater factor in the future. Recent droughts in various parts of the country emphasized our great dependence on ground-water, not only for wells but for supplying springs and surface-streams. They also stressed the need for a more comprehensive program of water-conservation and artificial replenishment of ground-water supply in areas of over-draft.

Fortunately, in many sections of the West, Nature has created large underground reservoirs by filling deep basins with porous alluvial material. These natural underground reservoirs regulate the water-supply derived from erratic precipitations by accumulating and storing the water of wet years for use in dry periods. The storage-capacity of underground reservoirs of this character is enormous in comparison with that of artificial surface-reservoirs. These underground basins are replenished by the percolation of rain or snow falling directly upon the valley-floors, seepage from streams traversing the valleys, flood-waters from mountain-areas discharging over alluvial fans, artificial water-spreading, return-waters from irrigation, seepage from canals, and in other ways.

Some of these underground storage-reservoirs contain the equivalent of many years of rainfall on their intake-areas. The supply, when exhausted below economic pumping-level, may require many years for its restoration to its original natural level. Artificial replenishment by water-spreading and other means may be desirable; also, the stimulation of natural replenishment by reducing runoff and losses by evaporation and transpiration, and by maintaining the soil in a condition of maximum absorptive capacity.

Our symposium on "Contribution to ground-water supplies" will deal primarily with replenishment of ground-water basins. It may be segregated into two parts: (1) Artificial replenishment, such as by water-spreading, and (2) natural recharge, such as by direct contribution from rainfall, percolation from surface-streams, and movement of ground-water.

Artificial replenishment

Until recent years, very little research had been done on water-spreading, although it has been practiced in California for the past 40 years. Water-spreading may be accomplished by diversion of surface-waters to adjacent lands where infiltration is increased through spreading by means of ditches, furrows, basins, pits, or wells. It includes any artificial means employed to increase percolation to underground reservoirs for the purpose of storing water for subsequent withdrawal.

A survey in several Western States shows that under favorable conditions depleted ground-water supplies can be recharged by water-spreading.

Southern California furnishes the best examples of well-developed spreading-systems. Some of the important spreading-grounds in southern California are the Santa Clara River, San Fernando Valley, Arroyo Seco, San Gabriel River, San Antonio Creek, Cucamonga Creek, Lytle Creek, Devil Canyon, City Creek, Santa Ana River, Mill Creek, Santiago Creek, and Whitewater River. Spreading works are being operated by various organizations such as water-districts, water-conservation associations, cities, and mutual water-companies. Valuable research studies are being carried on by A. T. Mitchelson and Dean Muckel of the Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture; V. M. Freeman of the Santa Clara Water-Conservation District of Ventura County; D. A. Lane of the City of Los Angeles Department of Water and Power; and others.

At a conference on water conservation (Report on Progress Conference on Water Conservation, Los Angeles, California, March 13-14, 1935, by Committee on Conservation of Water, Irrigation Division, Amer. Soc. C. E., December 1935) held in Los Angeles, March 1935, by the Committee on

Conservation of Water of the Irrigation-Division, American Society of Civil Engineers, the principal conclusions drawn from a paper presented by Kenneth Q. Volk, entitled "Economic limits of conservation of flood-water by spreading," may be summarized as follows:

(a) Artificial spreading of flood-water is beneficial. However, no general rules can be laid down for location, design or type of spreading-works as each area is an independent problem. Spreading of flood-water should not be done to the extent that a major portion of the additional conserved waters are lost through evaporation by increased areas of high ground-water.

(b) Ground-water storage with limited surface-storage is generally more economical than surface-storage only.

(c) Permanent diversion-structures adequate to withstand capital floods are essential for diversion of flood-water to spreading-areas in order to protect lower lands. Adequate provision should be made for returning uncontrolled flood-waters to main channel.

(d) It is uneconomical to provide for 100 per cent conservation of flood-waters. Occasional flushing of channels by major floods is necessary and physically unpreventable.

(e) Properly designed spreading-works, even if designed without economic limitations, are not a factor in the protection of life and property from damage by capital floods.

Several different methods may be employed in effecting artificial replenishment of ground-water supplies. These are described in papers by Fred Tibbetts, V. M. Freeman, and Dean Muckel, which are published in the present Transactions.

Natural recharge

The percolation from surface-streams is discussed in a paper by Raymond A. Hill and N. D. Whitman. A résumé of a paper by O. E. Meinzer on "Movement of ground-water," originally presented at the meeting of the American Association of Petroleum Geologists in March 1933, was read at the Pacific Coast meeting by Harold Troxell. Further information on this subject is given in United States Geological Survey Water-Supply Paper 494, "Outline of ground-water hydrology," by Mr. Meinzer.

Another contribution to ground-water supplies which should not be overlooked is the replenishment by percolation of rain falling directly upon the valley-floors. This factor is important in some areas. The problem of using the given supply of rainfall to the best advantage is one that has been given particular attention in recent years. The rain-water must be held on the area where it falls if serious runoff and erosion are to be prevented.

For several years the Division of Irrigation of the Bureau of Agricultural Engineering, United States Department of Agriculture, has studied the disposition of rainfall in its various phases after it falls on the surface in the valley-areas of southern California. Some of the results have been published (California State Bull. No. 33, "Rainfall-penetration and consumptive use of water in Santa Ana River Valley and Coastal Plain," by Harry F. Blaney, C. A. Taylor, and A. A. Young, 1930; also California State Bull. No. 46, a reprint of Chapter VI, "Rainfall-penetration," by Harry F. Blaney, 1933). Losses occur by surface-runoff, by evaporation from the soil-surface, and by transpiration from plants. A part of the water may penetrate below the reach of plant-roots and percolate downward to underground levels where it adds to the supply available for pumping.

The penetration of any one season's rainfall depends on the initial moisture-conditions in the soil at the beginning of the rainy season and the amount of evaporation and transpiration occurring during that season. These factors vary with the type of vegetative cover. For example, citrus trees are shallow-rooted and cause a small initial deficiency of soil-moisture, while deciduous trees and native brush are deep-rooted and use the soil-moisture to greater depths, thus causing a large initial moisture-deficiency. Soil-moisture studies are relied upon to determine values for the initial moisture-condition at the beginning of the rainy season and subsequent evaporation- and transpiration-losses. With these factors known, the rainfall penetrating below the root-zone can be calculated.

Evaporation-loss after a rainstorm is influenced by many factors such as temperature, wind-movement, soil-type, kind of vegetation, interception, periods between storms, etc. Observations made in southern California indicate that (a) the average evaporation-loss from the top soil is about one-half inch after each rainstorm, (b) the average transpiration for the winter for active agricultural crops is about one inch per month, and (c) the average winter evaporation-transpiration rate per month for grass and weeds is about two inches and for brush 2.4 inches.

The amount of rainfall penetrating below the root-zone for a typical station in Ventura County with a total seasonal rainfall of 15.05 inches for the year 1930-31 is estimated for different crops as follows: Citrus, cover cropped usual practice, 1.9 inches; deciduous, cover cropped, zero; beans, irrigated, 5.6 inches; beans, non-irrigated, 3.6 inches; grain, non-irrigated, zero; bare land, 6.6 inches; grass and weeds, zero; brush, zero. For the same station with a total seasonal rainfall of 21.71 inches for the year 1931-32, the amount of rainfall penetrating below the root-zone is estimated as follows: Citrus, cover cropped usual practice, 6.2 inches; deciduous, cover cropped, 2.7 inches; beans, irrigated, 10.7 inches; beans, non-irrigated, 8.7 inches; grain, non-irrigated, 5.7 inches; bare land, 11.7 inches; grass and weeds, 2.9 inches; brush, 0.7 inch.

The same total seasonal rainfall may give entirely different penetration due to varying intensity and distribution of storms. Irrigation during winter also varies with the season and influences the amount of penetration.

Division of Irrigation, Bureau of Agricultural Engineering,
U. S. Department of Agriculture,
Los Angeles, California

WATER-CONSERVATION PROJECT IN SANTA CLARA COUNTY

Fred H. Tibbetts

General description of Valley

The Santa Clara Valley Water-Conservation District is an area of about 130,000 acres comprising approximately the level floor of the main portion of Santa Clara Valley--the southward extension of San Francisco Bay. Except for perhaps ten per cent of the Valley covered by urban development, it is nearly all under intensive cultivation, with approximately three-fourths of the area in deciduous fruits, mostly prunes and apricots and with most of the balance in vegetable and truck gardening.

The assessed valuations in the District are about $85,000,000, and the total population about 110,000, including the City of San José. The average orchard holding probably does not exceed 15 acres.

Geological formations

Santa Clara Valley is an extension southward of San Francisco Bay and at least the lower end has probably been repeatedly alternately above and below sea-level. The level floor of the Valley, which is composed of silt, sand, clay, gravel, etc., has been washed down from the Franciscan shales and sandstones which surround it on three sides. The Franciscan formations are of great age and much broken and shattered by repeated faulting and by serpentine intrusions. Two of the major breaks in the California surface-topography, the San Andreas and the Hayward faults, movements along which have caused severe earthquakes during recent times, pass close to the western and eastern edges of the Valley.

Much the largest of the Valley's tributary streams, the Coyote River has worked down into the Hayward Fault. The flood-flow from this stream must be conserved if agriculture is to be preserved in Santa Clara Valley and hence it was found necessary to build the largest of the dams, straddling the Hayward Fault, and on what is probably as poor a foundation upon which a large dam ever was built.

The fill comprising the valley-floor, probably to a depth of several hundred feet, is a mixture of materials washed down from the surrounding mountains and is heavily interlaced with water-bearing gravel-strata of varying thickness. A study of some hundreds of well-logs spaced as uniformly as possible over the Valley indicates that about ten per cent by volume of the total valley-fill is composed of water-bearing gravel or sand. These water-bearing materials or aquifers seem to be buried stream-channels of much the same character as the gravel- or sand-layers a few feet in thickness found at the bottom of the present active streams. They radiate out from large deposits of gravel and boulders which constitute the alluvial cones of the present streams, and radiating out in such a manner they follow roughly the general direction of the present surface-drainage and interlace and overlap to a very large extent. The aquifer material, just like that found in the beds of the present streams, is quite open and porous.

As the streams have repeatedly abandoned their channels during the gradual upbuilding of the Valley, these very porous gravel- and sand-aquifers eventually become buried in silt and clay which, although not watertight, is nevertheless more impervious than the aquifers themselves. Engineering reports in the past have estimated the volume of this aquifer material from available well-logs, and in so doing have probably overestimated the same.

Wells which penetrate one or more of these aquifers are, of course, "good" wells and, as the Valley develops, the neighbors tend to bore new wells in the same vicinity in which "good" wells are known to exist. Wells which strike no aquifer material are "dry" wells and tend to be abandoned or forgotten, and the neighbors in boring new wells tend to stay away from the vicinity of such "dry" wells.

In a very extensive investigation of the Mokelumne River flood-plane made by the East Bay Municipal Utility District, this tendency for the wells to group along the line, and in the vicinity of ancient buried channels, was quite marked.

In a valley of this type, serious errors may be involved in the method most common in the past of estimating the change of ground-water storage during a season, or from one season to another, from well-measurements. A large portion of the total volume between the ground-water levels at the beginning and end of a season and between wells may have changed its total storage-water content but little.

Supposing two wells are 1000 feet apart, both of them penetrating the same aquifer or aquifers supplied from the same sources, and the well-measurements show that from the March high to the October low these wells have dropped ten feet, then the assumption is that the ground-water storage in the 1000 feet between the wells has been over-drafted to the extent of ten per cent of its total volume. As a matter of fact, most of this 1000 feet may be clay or fine silt. Tests in the laboratory made in determining the suitability of some of this material for constructing dams show that water may not move through it even at 100 per cent gradient more than four or five feet per year. Instead of taking eight months, then, for the ground-water stored in the assumed clay-area between the wells to drain into the wells and be pumped out, it would take 100 years to accomplish this result. It is the writer's belief that the amount of loose material, water-bearing in the practical sense that it can within short periods of time, say annually, store water and give it up the following season to wells, has been generally overestimated.

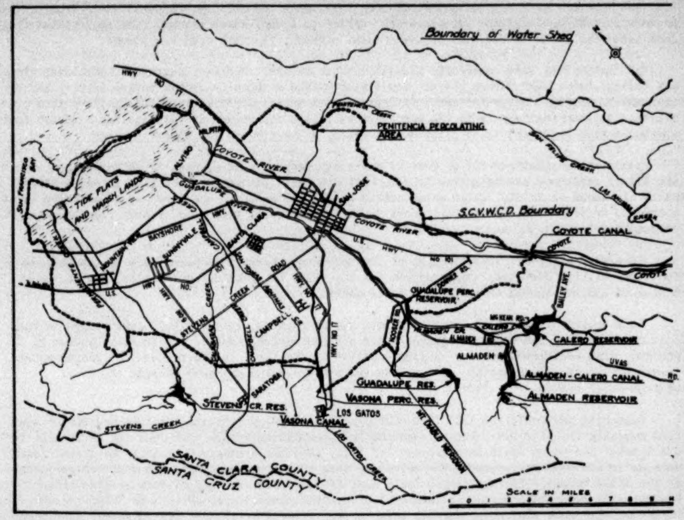
About the lower 40 per cent of the Valley, including generally the area northward from San José, seems to have repeatedly alternated from above to below sea-level. There is a thick blanket of impervious clay and the aquifers, which are ancient river-channels, seem generally to have pinched out at the lower ends in this impervious clay. These aquifers being buried in material less pervious than themselves and heading up into the gravel-cones into which water is poured as the surface-drainage debauches onto the valley-floor, tend to develop pressure under the marine clays where the area is artesian and, before the period of general overdraft, the pressure was great enough so that the water in wells rose above the natural surface of the ground.

Into this area, formerly artesian, whose upper limits are rather closely determined, water-pressure is quickly transmitted through the aquifers and this area is therefore subject to much more rapid and greater fluctuations in well-measurements at least, if not in the general water-plane, than the areas higher up. This fact has probably led in the past to overestimates of the overdraft. A very considerable portion of the recorded well-fluctuations represent merely variations in pressure rather than variations in volume of water stored underground.

If, as believed, the aquifers pinch out in the marine clays at the lower end of the Valley, then the underground storage-basin is enclosed on three sides by the surrounding mountains and escape of water to the northward is prevented as the aquifers or water-bearing material pinch out into the impervious clays below the level of the Bay. From this underground storage-basin there is, therefore, little marginal or terminal loss.

Irrigation

Nearly all of the area in the District is now irrigated by wells and much of the domestic supply for the urban areas is similarly obtained. There are over 2000 pumping-plants in operation. The power-company's records of agricultural power-consumption within this area, together


Boundary of Water Shed
HWY NO 17
PENITENCIA CREEK
PENITENCIA PERCOLATING AREA
SAN FELIPE CREEK
LAS ANIMAS CREEK
SAN FRANCISCO BAY
TIDE FLATS AND MARSH LANDS
ALVISO
MILPITAS
COYOTE RIVER
GUADALUPE RIVER
SAN JOSE
S.C.V.W.C.D. Boundary
COYOTE RIVER
COYOTE CANAL
COYOTE
U.S. HWY NO 101
BAYSHORE
MOUNTAIN VIEW
SUNNYVALE
SANTA CLARA
HWY
SAN TOMAS ROAD
STEVENS CREEK
CAMPBELL CR.
HWY NO 17
GUADALUPE PERC. RESERVOIR
ALMADEN CR.
ALMADEN
CALERO
CALERO RESERVOIR
UVAS RD.
ALMADEN-CALERO CANAL
ALMADEN RESERVOIR
GUADALUPE RES.
VASONA PERC. RES.
STEVENS CR. RES.
SARATOGA
LOS GATOS
VASONA CANAL
LOS GATOS CREEK
STEVENS CREEK
SANTA CLARA COUNTY
SANTA CRUZ COUNTY
SCALE IN MILES
0 1 2 3 4 5 6 7 8 9 10

with measurements showing the average lift of water, furnish a rather satisfactory check upon the relative use from year to year of pumped water for irrigation. Since the beginning of the permanent recession of the water-plane, apparently about 20 years ago, pumping-lifts have increased 100 feet or more and the cost of pumping has increased about $665,000 annually for power alone.

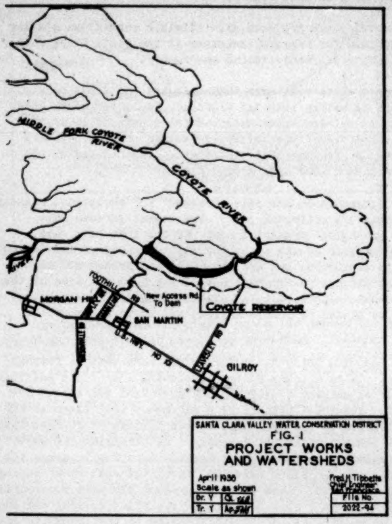
The duty of water for irrigation of this dominantly orchard-area is about one and one-fourth feet. The irrigation-season is long, pumping beginning shortly after the cessation of the rains in spring and continuing until late in the fall. There is a marked tendency in the last few years to change farming from deciduous orchards to truck gardening--berries, cabbages, peas, spinach, and the like. The truck gardens, as well as the urban areas, require somewhat more water than the orchards--not a great deal more, but through a longer season.

Decline of water-table

The fairly steady decline in the water-table for the last 20 years was during a period of increasing use of water and synchronized with a period of sub-normal rainfall and runoff, and hence recharge from runoff. Whether the decline is permanent and, if so, whether it is due chiefly to the subnormality of the rainfall and runoff can probably be determined accurately when we have 1000 years or more of records.

Engineers have stressed too much determinations of average rainfall or runoff. If an orchard-area, requiring $1000 or so an acre to bring it into bearing, has insufficient water during a dry cycle, or even during a year or two, to keep it alive, then it does not help the orchard any more than it would a human being under similar circumstances to demonstrate scientifically and conclusively that its average water-supply is sufficient.

The California State Division of Water Resources, in its Bulletin No. 42 on Santa Clara Valley, concludes that in an average season there is sufficient water, and hence the unthinking might conclude that there is no permanent decline in the water-plane or, perhaps, might even go further and question the necessity for remedial measures. While this is of scientific interest, it has nothing whatever to do with the economics of remedial measures under construction by the present District, because of the decline of over 100 feet, which has occurred in the last 20 years, causing an increase in the farmers' power-bills for pumping, equal to about ten times the



SANTA CLARA VALLEY WATER CONSERVATION DISTRICT
FIG. 1
PROJECT WORKS AND WATERSHEDS
April 1936
Scale as shown
Fred H Tibbetts
Chief Engineer
San Francisco
File No. 2022-94

interest on the cost of the remedial measures, and which has caused the farmers to spend two or three times as much as the total cost of the construction works for additional pumping-machinery, and has caused the Governor of the United States Farm Credit Administration a short time before the bond election to state that Federal farm credit could not be expected in a district where the water-table had fallen 90 feet in 15 years and nothing was being done about it.

About the time the remedial measures began to operate, the water had been pumped below sea-level in nearly half of the Valley, and in the District and in adjacent areas, salt and boron were being pumped from the lower strata, and the orchards were threatened with destruction.

The overdraft in the last 15 or 20 years in the Santa Clara Valley has been variously estimated from 25,000 to 40,000 acre-feet per annum. These estimates have been made by assuming that replenishment comes entirely from stream-bed percolation; that is, that there is no rainfall-penetration and that the overdraft can be estimated from well-measurements and estimates of the specific yield in the volume of material through which the water-plane, as determined by well-measurements, has dropped.

In the State Division of Water Resources' investigations of the water-plane, contours are drawn from well-measurements taken at convenient times, generally intended to approximate the high or low, and the water between the contours is computed from the change in ground-water storage-volume multiplied by "10.6 per cent voids, as was done in Water-Supply Paper 519 of the United States Geological Survey."

Two serious errors may be involved. The precipitation on the valley-floor, about 15 to 17 inches, probably never reaches the ground-water plane. It is absorbed as it passes through the surface-soil, part of it is immediately evaporated and the remaining part, a little lower down, is grabbed by the tree-roots and passed on to leave the vicinity by transpiration. There always seems to be an extensive dry zone of soil between the ground-water plane and the tree-roots. Around the rim of the Valley, however, especially on the west side, the precipitation is very much greater and there is a large area of porous, gravelly "Santa Clara" geological formation dipping gently under the valley-floor. Especially in dry years, the runoff in relation to the precipitation is much less on this side of the Valley and, while a part of the difference might be accounted for by the heavier growth of forest, it seems to the writer that the bulk of the difference is rainfall-penetration absorbed in the hills around the rim of the Valley, and passed under the valley-floor to ground-water storage.

Runoff and waste

Fairly accurate data are available on the total runoff into the valley-floor for some 30 years. The runoff in each of the streams has been estimated, as is usual in such cases, from accurate long-time measurements on some of them, including the largest, from additional rainfall-records and from the United States Geological Survey contour-maps. The writer's estimate of the average total runoff into the valley-floor is about 202,000 acre-feet per annum, of which about 76,000 acre-feet is naturally absorbed and 126,000 acre-feet wasted into the Bay. With the total storage proposed, though not all included in the present project, the present approximate proportions, in which two-thirds of the natural supply is wasted and one-third used, could be reversed to about two-thirds used and one-third wasted.

Construction-program (see Fig. 1)

Detention-reservoirs--Like all water-development projects with climatic conditions similar to this, the large bulk of expenditures proposed for remedial measures in the Santa Clara Valley are intended to correct the highly variable rate of precipitation and runoff.

Little of the tributary watershed reaches elevations over 2500 feet and the great bulk of the runoff occurs in short, sharp floods and is wasted into San Francisco Bay a few hours after rain has occurred. The primary requirement to salvage waste-water is the construction of detention-reservoirs in the foot-hills near the rim of the Valley, to detain the flood-waters and release them from the reservoirs at rates so reduced that the detained flood-water is all absorbed in stream-bed percolation and thus passed into underground storage.

Five principal reservoirs have been constructed on the main streams. For geological reasons previously discussed, the foundations for dams are uniformly poor. The dammed streams have found their way either into fault-lines or geological contact-lines. Of the five main dams, there is complete geological non-conformity at four of the sites, on the two sides of the stream. The foundation-materials are not only deeply weathered, but are shattered and broken and highly variable in quality. Roll-fill dams of conventional design have been constructed at five of the sites, generally from 100 to 140 feet in height, with particular attention paid during construction to laboratory-control of the material as placed to insure maximum and uniform compaction and uniform moisture.

The largest of the dams is the Coyote Dam, now being built for 30,000 acre-feet of storage and readily enlargeable to 45,000 acre-feet. It is a freak design, including all of the possible safety provisions proposed by quite a number of eminent consulting engineers and geologists retained by the District and by the State. The resultant product is a dam about four times as big as the standard on the rest of the job, built 100 to 160 feet wide on top instead of 20 feet like the others, and built in the reservoir-site instead of at the dam-site. It straddles the Hayward Fault, which is parallel to and comparable to the San Andreas Fault. This Fault, since its youthful days some millions of years ago, has hunched along some 1400 feet; the west side, facing the San Andreas Fault, moving upward and to the north. Some of this movement has been accompanied by earthquakes, but quite a good deal of it has been a slow movement in the plastic, very old and soft Franciscan shales. The dam should be able, without any possible danger to the community below, to stand without injury at least three times as big an earthquake as has ever occurred and probably all of the earthquakes which will occur until the reservoir is silted full.

The central earth roll-filled core of the Dam is blanketed both upstream and downstream by blankets of gravel ten feet thick at the top and 90 feet thick at the bottom, and outside of these by similar blankets of heavy rock-fill.

Most of the structure extends upstream from the site of the Dam in the Canyon and is built in the reservoir and blocked in at the abutments against the rock-points which form the site of the Dam in the Canyon. The gravel and rock-fill blankets, in the opinion of experts, in case the reservoir is full and the Dam saturated when a big earthquake comes, will hold the earth-core in place and the latter will hold the water. The gravel with the heavy rock on top of it, in case the Dam is stretched by the earthquake endways so that cracks open up, will fall into the cracks and prevent the water rushing through; and the bulk of the structure being up in the reservoir, even if badly shaken, could merely be pushed up against the abutments and could not slip or slide downstream.

The writer apologizes for not being enough of a geologist to give a more plausible account of what might happen to this Dam during an assumed earthquake, but at any rate the cost of the structure is satisfactory to everybody but the owners and the amount of unemployment relief is much greater than if the Dam had been built at the site of the Dam instead of in the reservoir.

Stream-bed improvements--The second general class of construction-works is intended to artificially increase the natural rates of percolation, particularly in the stream-beds. Low dams are constructed across the creeks out in the valley-floor, with the object of leveling up the creek-bottoms, and thus causing a given flow of water to cover a larger area. A few low buttress-type, reinforced-concrete dams have been built, but in the main the stream-bed improvements consist of "sausage-dams," constructed of Page wire fencing held in place by steel fence-posts driven in the gravel creek-beds. The height of these dams is generally about two and one-half to three feet (see Fig. 2). Most of these have been built in areas in which measurements have shown stream-bed percolation rates to be high, such areas generally being on the gravel-cones where the streams enter the valley-floor. This type of construction is quite cheap, the dams in place complete costing about $6 per lineal foot.

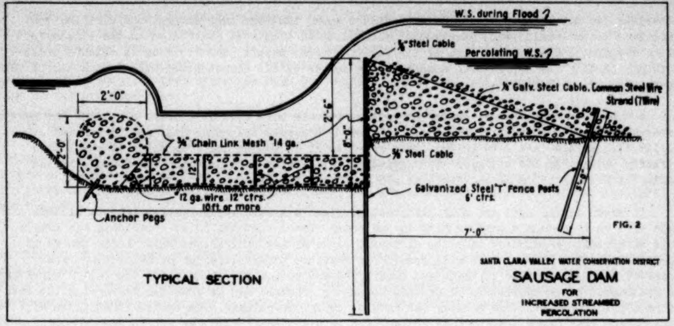

W.S. during Flood
Percolating W.S.
⅜" Steel Cable
⅜" Galv. Steel Cable. Common Steel Wire Strand (7 Wire)
2'-0"
2'-6"
6'-0"
2'-0"
¾" Chain Link Mesh #14 ga.
12"
⅜" Steel Cable
12 ga. wire 12" ctrs.
10 ft. or more
Galvanized Steel "T" Fence Posts 6' ctrs.
Anchor Pegs
5'-6"
7'-0"
TYPICAL SECTION
SANTA CLARA VALLEY WATER CONSERVATION DISTRICT
SAUSAGE DAM
FOR
INCREASED STREAMBED
PERCOLATION

FIG. 2

We believe that the higher up on the stream the dams are placed, the wider will be the underground distribution resulting therefrom. Measured percolation-rates will ordinarily vary from two feet to as high as 14 or 15 feet per day, that is, two acre-feet per acre per day, etc. These percolation-rates are not constant, even in the same location. The percolation-basins tend to silt up, and we are developing a practice of furrowing them annually. When supplied by reservoir-releases, the water is de-silted and hence clear. If the water is not impounded more than two or three feet deep, as on most of the streams, then the bottom-velocity during floods seems to be high enough to scour the gravel-beds clean again.

One of the main percolating structures is at the extreme upper or southern end of the District, on the main river, the Coyote. This is a reinforced-concrete structure with movable superstructure and radial crest-regulating gates permitting the water to be raised about ten feet, covering an area of about 33 acres, on a gravel-cone in which the gravel is at least 90 feet deep. This percolating bed can be filled during the summer by reservoir-releases from the 30,000 acre-feet reservoir, and hence it should be operated only after the flood-season and supplied only with de-silted reservoir-releases. This structure has been in operation for two seasons, with measured rates of absorption of about two and one-half feet per day or 75 to 100

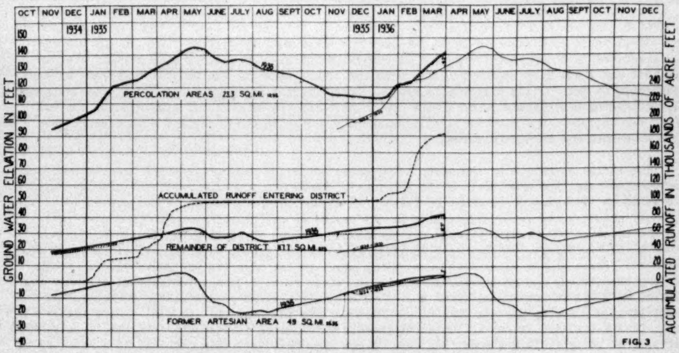


FIG. 3

SANTA CLARA VALLEY WATER CONSERVATION DISTRICT
HYDROGRAPHIC DEPARTMENT

GROUND-WATER FLUCTUATION IN PERCOLATION-AREAS, FORMER ARTESIAN AREA, AND REMAINDER OF DISTRICT acre-feet per day total. Ground-water contours would indicate that underground distribution from this point should reach nearly half the Valley in time. It is located on the stream in which originates over 60 per cent of the Valley's total supply, and it alone is capable of absorbing annually the approximate amount of the volume of the Coyote Reservoir storage and of the present valley overdraft.

A number of "off-channel" water-spreading projects have been developed. In these the water, reservoir-releases or natural flow, is diverted by concrete diversion-dams and is carried across country in surface-canals to gravel-areas on which it is ponded and from which it percolates directly to underground storage. The aggregate capacity of such off-channel projects in the Valley is now about 300 second-feet, or 600 acre-feet per day.

It seems likely that the most difficult problem in a water-conservation project of this type will be to secure a uniform rise in the water-plane, that is, to so distribute the available water that percolation into the different parts of the underground water-basin can be so controlled that a uniform rise will result, or that the water-plane can be brought up first where it has declined the farthest and conditions are most acute, such as in the 40,000 acres or so now pumped below sea-level. A certain measure of control can be effected by varying the rate of reservoir-releases. The greater the rate of reservoir-release, the farther downstream will percolation take place. Additional control can be effected through the off-stream percolating projects, but final control can probably be obtained only by construction of a peripheral canal around the rim of the Valley. In the Santa Clara Valley such a canal is proposed, particularly because about 60 per cent of the runoff originates in the Coyote River southeast of the Valley, whereas two-thirds of the Valley's overdraft, including the areas which are suffering most, is on the diagonally opposite northwest corner of the District, bordered by shallow watersheds with meager runoff available.

Operating results

During the first year of construction on the project, the season of 1934-35, the rainfall was exceptionally well distributed, including very beneficial and unusually late, heavy rains. The District's percolating works had been completed and were in use, so that with the total inflow into the Valley of about 99,000 acre-feet, but 28,500 acre-feet were wasted. This present season, however, the bulk of the runoff was concentrated during two and one-half weeks of continuous precipitation. The District's two largest reservoirs, the Coyote and the Calero, were not yet complete, so it was not possible to use them to their full efficiency. Nevertheless, the Government's gagings indicate that had it not been for the reservoirs, approximately two-thirds of the water-supply for this season to date would have been wasted.

During the prolonged flood-stages of February, when most of this season's runoff was concentrated, the waste in the entire Valley amounted to only 31 per cent of the seasonal runoff, whereas it would have amounted to 68 per cent had there been no storage. Due to the storage, the amount of this concentrated period of runoff, which has and will be made useful, will be 69 per cent and would have been but 32 per cent had it not been for the control exercised by the reservoirs on most of the principal streams. These figures check rather closely with the general engineering conclusions prior to the construction of the reservoirs, that without control about two-thirds of the water-supply is wasted and one-third used, whereas with control two-thirds is used and one-third wasted.

The steady operation of the percolating areas builds up vast underground water-mounds which, during last year, had been built up to a volume of about 100,000 acre-feet, the average rise in the wells in this area being about 50 feet. The volume of these mounds, superimposed above the ordinary ground-water level, aggregated at the height of the season about 100,000 acre-feet, and the measured percolation through the stream-beds on top of these ground water-mounds was about 10,370 acre-feet, indicating a specific yield in the ground water-mounds of at least ten per cent. These ground water-mounds, however, were, in the main, in the gravel-cones of the streams themselves, and as previously discussed, these results do not indicate at all that the average material in the valley-floor will have a specific yield or "available porosity," at least available during any one season, of anything like the same ten per cent. As a matter of fact, during the last season the total stream-bed percolation in the entire valley, with over 90 per cent of it actually measured, was only 70,500 acre-feet, and this resulted in a recovery of the water-plane occupying a volume of about 2,600,000 acre-feet, apparently indicating a practical available porosity of less than three per cent for the Valley as a whole. This deduction is subject to very important errors, one of which may be the unmeasured contribution from rainfall-penetration on the western side of the Valley, and the other the great error inherent in basing this type of conclusions from well-measurements alone.

Just as soon as the stream-flow ceased, the artesian area dropped down very sharply, the ground water-mounts flattened out gradually until the beginning of new runoff in 1936, but as they flattened out they held up the central or main portion of the District so there was comparatively little midsummer drop, the average low point reached in the central portion of the District being but five feet below the high point and at least ten feet higher than the low point of the previous year.

It would appear that as soon as water covered a gravel-cone and started filling up the aquifers around the rim of the Valley, these aquifers may have immediately transmitted pressure, enclosed as they are in silt and clay, to the area formerly artesian, with the result that wells in this area rose 40 to 50 feet in a few days or weeks and stayed up as long as the pressure was held up by the presence of water on the surface of the gravel-cones at the head of the aquifers (see Fig. 3).

It may be that as soon as sufficient runoff is available, reservoir-releases can prolong the natural runoff-season so that, throughout the entire irrigation-season, water can be held on the percolation-works above the surface of the gravel-cones of the main streams, and that this will hold up to former levels the 40,000 acres formerly artesian and will gradually bring up to somewhere near former levels the 80,000 acres comprising the main or central portion of the Valley.

On March 15, 1936, the average water-level in the ground water-mounds was 7.6 feet higher than at the same date of the previous year, and the average water-level in the main or central portion of the Valley was 12.2 feet higher.

Chief Engineer, Santa Clara Valley Water Conservation District,
San Francisco, California

WATER-SPREADING AS PRACTICED BY THE SANTA CLARA WATER-CONSERVATION DISTRICT, VENTURA COUNTY, CALIFORNIA

V. M. Freeman

The Santa Clara Water-Conservation District was organized in 1928 under what is known as the Water-Conservation Act of 1927, Assembly Bill No. 233, and is, therefore, a legal entity. The assessed valuation of the District is approximately $20,000,000 and the boundaries embrace 110,000 acres of lands situated in the Santa Clara River Valley and the Oxnard Plain, in Ventura County, California. The lands in the incorporated cities of Oxnard, Santa Paula, and Fillmore are not in the District. The maximum annual tax which can be levied by the District is 15 cents on the $100 of assessed valuation of land and improvements. The District was organized for the purpose of protecting water-rights and the conservation of the waters of the Santa Clara River and its tributaries. The District is dependent almost entirely on ground-water as a source of supply for domestic and irrigation purposes.

Our organization was the first agency to practice water-spreading in Ventura County and our success is due in no small part to the valued council of Harold Conkling, Deputy State Engineer, and R. H. Jamison, Senior Hydraulic Engineer, State Division of Water-Resources, regarding the proper location of our spreading-works.

Having had no previous experience in the design and operation of spreading-works and due to the fact that our funds are limited, we have felt our way along rather carefully. Percolation-tests were made at all tentative spreading-ground locations prior to construction. This procedure was made possible by the cooperation of water-companies having distribution-mains or ditches near the proposed spreading-ground locations. We operate three spreading-grounds located near the cities of Saticoy, Santa Paula, and Piru.

Saticoy Spreading-Ground--The Saticoy Spreading-Ground is located on the south side of the Santa Clara River and east of the Saticoy Bridge. Water is diverted from the Santa Clara River by temporary earth-dams. It is conveyed to the spreading-basins by 2600 feet of 60-inch reinforced-concrete pipe and 2700 feet of unlined canal. The capacity of the pipe-line and canal is 135 second-feet. The spreading-system consists of 33 basins, varying in size from 1.2 to 6.0 acres of wetted area. The total wetted area of the 33 spreading-basins is 97 acres. The top soil on which the basins are constructed has been classified as "Yolo fine sandy loam." The depth to ground-water beneath the basins at the beginning of a spreading-season has varied from 75 to 90 feet, since 1931. The lands occupied are under lease for a period of 20 years.

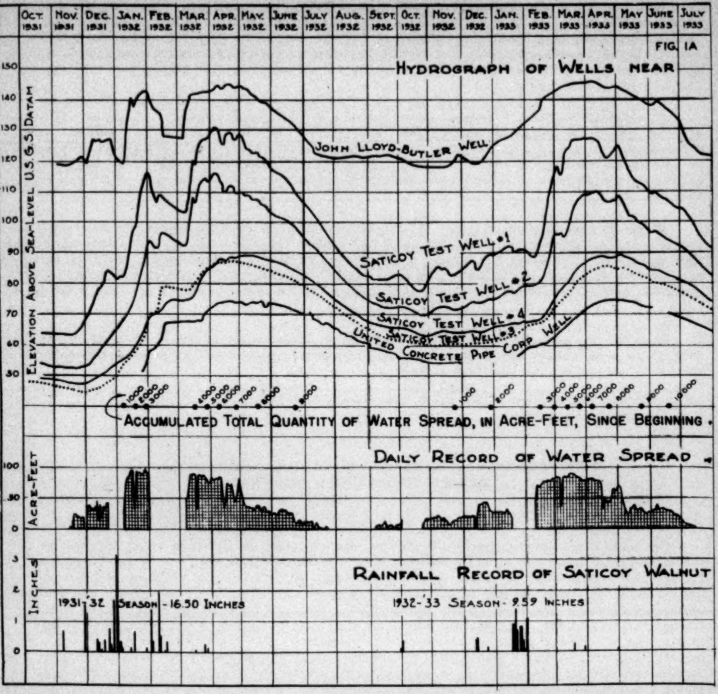


FIG. 1A

In 1931 the District drilled four test-wells adjacent to this spreading-ground. These wells were equipped with 8-day rational water-level recorders. The hydrographs of these wells are given in Figure 1 and show the fluctuation of the water-plane and the amount of water spread at the Saticoy Spreading-Ground.

In addition to the hydrographs of the four test-wells, this chart also shows the hydrographs of the John Lloyd-Butler Well and the United Concrete Pipe Company Well. The Lloyd-Butler Well is located near the upper basin and the United Concrete Pipe Company Well is located approximately 600 feet below the Last Basin. The static water-level in these wells is very sensitive to our spreading-operations and responds to any interruption or change in quantity of water being diverted into the basins. The following are ground-surface elevations in feet above sea-level at wells shown in Figure 1: No. 1, 143.09; No. 2, 140.26; No. 3, 137.25; No. 4, 143.16; John Lloyd-Butler Well, 151.10; United Concrete Pipe Company Well, 134.30.

Santa Paula Creek Spreading-Ground--The overflow-channels on the easterly side of the Santa Paula Creek debris-cone have been utilized for spreading-purposes each year since the fall of 1931. Water is diverted from the main channel of the Santa Paula Creek by means of a small rock-and-gravel dam and is conveyed to the overflow-channels by means of 700 feet of 30-inch reinforced-concrete pipe having a capacity of 25 second-feet. Ninety-seven small spreading-basins have been formed by the construction of loose rock check-dams in the overflow-channels. The total wetted area of these 97 basins has not as yet been developed. The top soil of the overflow-channels is of the river-wash type usually found on debris-cones having a fairly steep

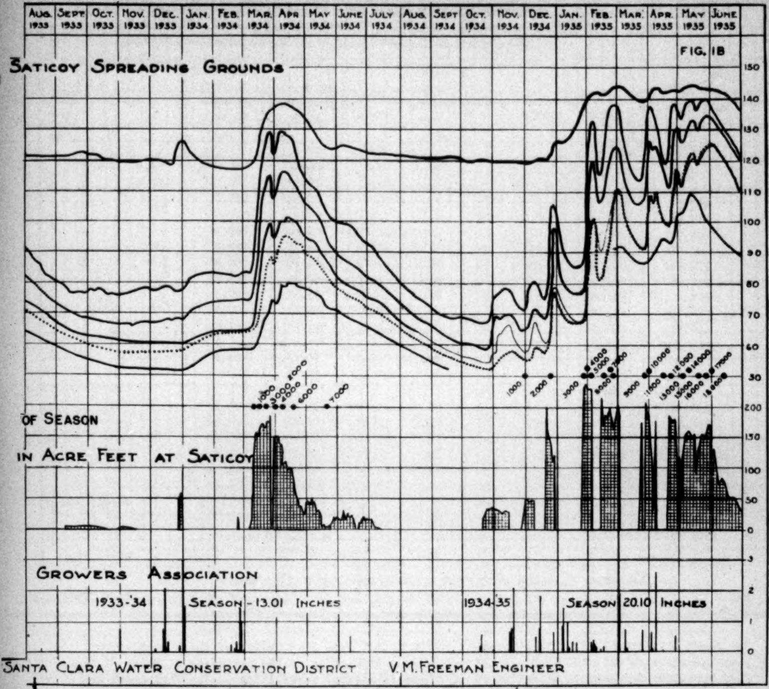


FIG. 1B

gradient. The depth to ground-water beneath the lower end of the spreading-ground is about 100 feet at the beginning of a spreading-season. The land occupied was leased by the District for a ten-year period.

Piru Spreading-Ground--This spreading-ground is located on the west side of the Piru Creek debris-cone south of the State Highway. Water is diverted from the main channel of the Piru Creek by rock-and-gravel dams of temporary construction. It is conveyed to the spreading-basins by 2000 feet of 48-inch reinforced-concrete pipe having a capacity of 80 second-feet. At the present time we have nine basins with a total wetted area of 43.2 acres. The top soil on which the basins are constructed has been classified as "Yolo gravelly fine sandy loam." The depth to ground-water beneath the basins at the beginning of a spreading-season has varied from 130 to 160 feet since 1932. The District acquired the fee title to the land occupied by this spreading-ground in 1930.

The C. S. Johnson Well located 2500 feet below the Piru Spreading-Ground was equipped with a Stevens water-level recorder, type L, October 1, 1931. The hydrograph of this Well is given in Figure 2 and shows the fluctuation of the water-plane and the amount of water spread at the Piru Spreading-Ground.

The elevation of the ground-surface at the center of the Piru Spreading-Ground is 660 feet above sea-level, and the elevation of the ground-surface at the Johnson Well is 647.8 feet. The hydrograph from September 1927 to October 1931 was plotted from occasional measurements made by

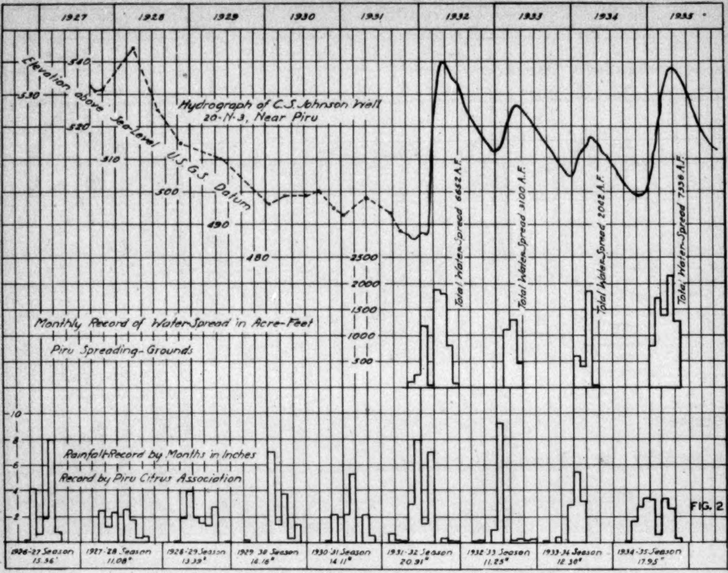


FIG. 2

SANTA CLARA WATER CONSERVATION DISTRICT

Chart showing Hydrograph of C.S. Johnson Well, Monthly Record of Water-Spread at Piru Spreading-Grounds, Rainfall-Record of Piru Citrus Association, from 1927 to date — V.M. Freeman, Engineer

the State Division of Water Resources and the District. The fluctuation of the ground-water plane as shown on this chart should not be entirely attributed to the spreading of water at the Piru Spreading-Grounds, as a portion of it is due to natural percolation in the Piru Creek and Santa Clara River channels during storm-flows.

The following is a brief statement of our method of procedure in spreading water. The Santa Clara River and its tributaries carry large quantities of silt and suspended matter during storm- or flood-flows. No attempt is made to spread water carrying more than 20 cubic feet of suspended matter per acre-foot. Water in our streams carries as high as 5000 cubic feet of suspended matter per acre-foot during peak-flows but generally the load of suspended matter reduces to 20 cubic feet or less per acre-foot in from two to ten days after the peak. Determination of the amount of suspended matter carried by the streams is made by the evaporation-method from samples collected in pint milk bottles by means of a sampler copied from the design used by the United States Geological Survey as described in Water-Supply Paper 636B. The sampler is used with weight, cable, and stay-line similar to current-meter suspension.

The spreading-basins of the Saticoy unit have not been cultivated or subsoiled since their construction, the natural growth of vegetation being left undisturbed.

The first unit of the Saticoy Spreading-Ground was constructed in the fall of 1929. To date the basins have not been cleaned and there is no noticeable reduction in the rate of percolation at the beginning of a spreading-season.

The Piru Spreading-Ground was constructed in the fall of 1931. The upper four basins were cleaned two years later, at which time a silt-deposit varying from two to four inches in thickness was removed.

Table 1--Santa Clara Water-Conservation District: Measurements of surface-flow of Santa Clara River at a point 2600 feet above Saticoy Bridge and at Montalvo Bridge, showing increased percolation after scarifying stream-channel

Date		Discharge 2600 ft east of Saticoy Bridge	Discharge Montalvo Bridge	Percolation	Estimated natural percolation	Hours	Total spread	Total spread	Accumulation
	1933	sec-ft	sec-ft	sec-ft	sec-ft		sec-ft	acre-ft	acre-ft
March	1 (a.m.)[a]	79.44	70.84	8.60	8.60	..	.....	......	....
	1 (p.m.)	70.92	62.51	8.41	8.41	..	.....	......	....
	7[b]	77.38	64.99	12.39	8.77	12	1.81	3.589	3.589
	8	.....	.....	.....	....	24	9.67	19.176	22.765
	9	74.68	50.49	24.19	8.47	24	15.72	31.173	53.938
	10	78.48	52.91	25.57	8.90	24	16.67	33.057	86.995
	11	79.58	55.04	24.54	9.02	24	15.52	30.776	117.771
	12	82.50	59.03	23.47	9.36	24	14.11	27.980	145.751
	13	72.77	49.16	23.61	8.25	24	15.36	30.459	176.210
	14	74.92	41.93	32.99	8.50	24	24.49	48.564	224.774
	15	71.18	37.64	33.54	8.07	24	25.47	50.507	275.281
	16	.....	.....	.....	....	24	26.92	53.382	328.663
	17	74.83	37.96	36.87	8.49	24	28.38	56.278	384.941
	18	70.09	37.33	32.76	7.95	24	24.81	49.198	434.139
	19	.....	.....	.....	....	24	21.49	42.615	476.754
	20	61.40	36.27	25.13	6.96	24	18.17	36.030	512.784
	21	63.44	33.27	30.17	7.19	24	22.98	45.569	558.353
	22	60.62	36.27	24.35	6.87	24	17.48	34.663	593.016
	23	59.96	32.21	27.75	6.80	24	20.95	41.544	634.560
	24	57.12	34.66	22.46	6.48	24	15.98	31.668	666.248
	25	55.91	30.90	25.01	6.34	24	18.67	37.023	703.271
	26	.....	.....	.....	....	24	16.87	33.453	736.724
	27	45.56	25.33	20.23	5.17	24	15.06	29.864	766.588
	28	.....	.....	.....	....	24	15.03	29.804	796.392
	29	43.71	23.75	19.96	4.96	24	15.00	29.745	826.137
	30	.....	.....	20.90	....	24	16.04	31.807	857.944
	31	.....	.....	21.84	....	24	17.08	33.870	891.814
April	1	40.98	18.21	22.77	4.65	24	18.12	35.932	927.746
	2	.....	.....	20.14	4.48	24	15.66	31.054	958.800
	3	38.07	20.56	17.51	4.32	24	13.19	26.156	984.956
	4[c]	.....	.....	18.93	4.64	24	14.29	28.337	1013.293
	5	.....	.....	20.35	4.96	24	15.39	30.518	1043.811
	6	.....	.....	21.77	5.28	24	16.49	32.700	1076.511
	7	.....	.....	23.19	5.60	24	17.59	34.881	1111.392
	8	36.20	11.59	24.61	5.92	24	18.69	37.062	1148.454
	9	.....	.....	26.03	6.24	24	19.79	39.243	1187.697
	10	.....	.....	27.45	6.56	24	20.89	41.425	1229.122
	11[d]	.....	.....	28.87	6.88	24	21.99	43.606	1272.728

[a] Measurements made before scarifying; estimated natural percolation of 11.34 per cent based on measurements made March 1, 1933.

[b] Started scarifying in river-bed March 7, 1933.

[c] Starting April 4, estimated natural percolation increased one per cent per day on account of warmer weather prevailing.

[d] Natural percolation estimated 19.34 per cent.

Water diverted to spreading-grounds is measured by means of Parshall flumes and rated canal-stations equipped with type-E, eight-day Stevens recorders.

Our field-force varies from three to five men depending upon the quantity of water being spread. At the Piru and Santa Paula spreading-grounds one attendant at each is on duty eight hours per day during the spreading-season. At the Saticoy Spreading-Grounds three men working eight-hour shifts are on duty when we are diverting 50 second-feet or more. When the head drops to less than 50 second-feet one man working 8 hours per day handles the work satisfactorily.

Another method of increasing ground-storage of water but not involving the use of basins consists of scarifying the stream-bed of the river. Current-meter measurements of the flow of the Santa Clara River from a point approximately 2600 feet above the Saticoy Bridge to the ocean

Table 2--Santa Clara Water-Conservation District: Measurements of surface-flow of Santa Clara River at a point 2600 feet above Saticoy Bridge and at Montalvo Bridge, showing increased percolation after scarifying stream-channel

Date	Discharge 2600 ft east of Saticoy Bridge	Discharge Montalvo Bridge	Percolation	Estimated natural percolation	Hours	Total spread	Total spread	Accumulation
1933	sec-ft	sec-ft	sec-ft	sec-ft		sec-ft	acre-ft	acre-ft
Dec. 19[a]	39.90	30.39	9.51	9.51	..	.....	......	....
20[b]	39.06	28.48	10.58	10.58	..	.....	......	....
21[c]	37.40	.....	15.29	11.22	24	4.07	8.071	8.071
22	35.74	.....	20.01	11.79	24	8.22	16.300	24.371
23	34.08	.....	19.08	12.26	24	6.82	13.524	37.895
24[d]	32.41	14.21	18.20	12.64	24	5.56	11.025	48.920
25	30.76	.....	17.22	12.92	24	4.30	8.527	57.447
26[e]	29.10	.....	16.29	13.09	15	2.00	3.966	61.413
1934								
Jan. 15[f]	77.40	65.30	12.10	12.10	..	.....	......	....
16[g]	71.66	63.66	8.00	8.00	..	.....	......	....
17	.....	.....	14.77	9.66	24	5.11	10.133	71.546
18	72.49	50.94	21.55	9.71	24	11.84	23.479	95.025
19	.....	.....	30.26	9.94	24	20.32	40.295	135.320
20	75.90	36.93	38.79	10.17	24	28.80	57.110	192.430
21	.....	.....	35.64	9.62	24	26.02	51.598	244.028
22	67.67	35.36	32.31	9.07	24	23.24	46.085	290.113
23	.....	.....	31.60	8.80	24	22.80	45.212	335.325
24	.....	.....	30.89	8.53	24	22.36	44.340	379.665
25	61.67	31.48	30.19	8.26	24	21.93	43.487	423.152
26	.....	.....	30.17	8.21	24	21.96	43.547	466.698
27	.....	.....	30.14	8.16	24	21.98	43.586	510.284
28	.....	.....	30.12	8.11	24	22.01	43.646	553.930
29	60.18	30.09	30.09	8.06	24	22.03	43.685	597.615
30	.....	.....	29.94	8.08	24	21.86	43.348	640.963
31	.....	.....	29.80	8.10	24	21.70	43.032	683.996
Feb. 1	.....	.....	29.66	8.12	24	21.54	42.714	726.710
2	60.80	31.29	29.51	8.15	24	21.36	42.357	769.067
3	.....	.....	29.99	8.26	24	21.73	43.091	812.158
4	.....	.....	30.47	8.38	24	22.09	43.804	855.962
5	63.39	32.45	30.94	8.49	24	22.45	44.518	900.480
6	.....	.....	30.23	8.41	24	21.82	43.269	943.749
7	.....	.....	29.52	8.33	24	21.19	42.020	985.769
8	.....	.....	28.81	8.25	24	20.56	40.770	1026.539
9	60.98	32.88	28.10	8.17	24	19.93	39.521	1066.060
10	.....	.....	26.79	7.92	24	18.87	37.419	1103.479
11	.....	.....	25.48	7.68	24	17.80	35.297	1138.776
12	55.54	31.38	24.16	7.44	24	16.72	33.156	1171.932
13	.....	.....	25.72	7.93	24	17.79	35.278	1207.210
14	.....	.....	27.28	8.41	24	18.87	37.419	1244.629
15	.....	.....	28.84	8.90	24	19.94	39.541	1284.170
16	69.97	39.56	30.41	9.38	24	21.03	41.702	1325.872
17	.....	.....	28.84	8.85	24	19.99	39.640	1365.512
18	.....	.....	27.27	8.32	24	18.95	37.578	1403.090
19	58.17	32.47	25.70	7.79	24	17.91	35.516	1438.606
20	.....	.....	.....	....	24	16.87	33.453	1472.059
21	.....	.....	.....	....	24	15.83	31.391	1503.450
22[h]	.....	.....	.....	....	14	8.63	17.113	1520.563

[a] Measured 23.84 per cent loss. [b] Measured 27.09 per cent loss. [c] Started work with tractor. [d] Measured. [e] Water spread in grounds. [f] From January 15, 1934, to end, natural percolation calculated at 13.40 per cent. [g] Started work with tractor. [h] Water turned in spreading-grounds.

Note: Storm of January 1, 1934, changed the natural percolation-factor.

show there is very little percolation in the stream-bed between these points after the peak storm- or flood-flow has passed. In order to salvage some of this water which wastes into the ocean, the District has been scarifying the stream-bed from a point 2800 feet above the Saticoy Bridge to a point approximately two miles below the Saticoy Bridge. This work is done after storms each year using a heavy road-scarifier drawn by a 20-horse-power Holt tractor. The edges of the stream and all riffles are scarified. The results of this work after storm-flows in 1933 and 1934 are shown in Tables 1 and 2. The total calculated induced percolation shown in Table 1 is 1272 acre-feet for the period March 8 to April 11, 1933. The total calculated induced percolation shown in Table 2 is 1520 acre-feet for the period December 21, 1933 to February 22, 1934.

In areas similar to that of the Santa Clara Valley, where there is a sustained flow in the streams after storms, or where stream-regulation has been provided, the writer is of the opinion that the depth to ground-water beneath a spreading-ground is as important a factor to be considered as the rate of percolation in the design and operation of spreading-works. Our experience indicates that the depth to ground-water at the beginning of a spreading-season is one of the fundamental factors affecting the capacity of a spreading-ground.

At the Saticoy location, where the ground-water plane was about 80 feet below the ground-surface at the beginning of the 1934-35 spreading-season, it was observed after spreading 13,000 acre-feet on 97 acres of basins there was a noticeable reduction in the rate of percolation per acre of wetted area. The spreading of this 13,000 acre-feet of water raised the ground-water plane beneath the spreading basins to within ten feet of the surface.

During the 1934-35 season from the latter part of October 1934 to the first of July 1935, a total of 18,917 acre-feet of water was spread at the Saticoy grounds. From the behavior of the works during the latter part of the season it is thought the capacity of the Saticoy Spreading-Works, as constructed, has a yearly capacity of about 200 acre-feet per acre of wetted area when the ground-water plane stands 80 feet below the surface at the beginning of a spreading-season.

During the 1934-35 season we spread a total of 30,411 acre-feet. The cost of material and labor incidental to the spreading-operations during the 1934-35 season varied from $0.145 to $0.203 per acre-foot with an average cost of $0.183 per acre-foot. The District's efforts have been modest as evidenced by the financial statement for December 27, 1927 to June 30, 1935. This shows total receipts from taxation of $124,633 and total disbursements of $119,208. Since its inception in 1928 our organization, up until June 1935, had spread a total of 98,166 acre-feet of water.

Santa Clara Water-Conservation District,
Santa Paula, California

SOME FACTORS AFFECTING THE RATE OF PERCOLATION ON WATER-SPREADING AREAS

Dean C. Muckel

There are four general methods of spreading water for storage, namely, (1) the basin-method, (2) the ditch-method, (3) flooding of undisturbed lands, and (4) delivery of water directly to the underground storage by means of wells, shafts, or tunnels. Each of these has its merits, and specific conditions govern its use. They are often used in combination with one another, and it is not uncommon to find all four methods utilized in a single system. As with other engineering work, local conditions must be considered in selecting the most suitable method.

In the design of a water-spreading plan, the engineer sets as his goal a system which will permit the greatest amount of water to percolate to the underground reservoirs in a given time from a given area. Time is especially important in southern California as the stream-flow during the spreading-season is flashy in character and of short duration. Area is more a matter of economics as the cost of the spreading-system increases with the area developed, and there are many locations where the land available for spreading-purposes is limited either by geological conditions or agricultural development.

It is, therefore, important that something be known of the conditions which lead to the highest percolation-rates. To determine these conditions the factors which affect the rate of percolation must first be fixed and evaluated. The Division of Irrigation of the Bureau of Agricultural Engineering undertook to do this and started active research-work on the problems in 1930 under the leadership of A. T. Mitchelson. It was determined that the primary work should be done on experimental plots under complete control and that later the studies should be extended to the larger areas where spreading is done under practical conditions.

After careful examination of conditions in the various areas where water-spreading was already being carried on, a plot was selected on the San Gabriel River debris-cone just north of the City of Azusa. The plot was selected at this point for four reasons: First, there was an adequate water-supply, perfectly controlled, for at least three months of the year; second, the soil was typical of that found on most water-spreading areas--not in the stream-bed proper; third, there was a fluctuating water-table during certain periods of the year; and, fourth, we had perfect cooperation from the people controlling both the land and the water.

Consequently, an area near the eastern edge of the debris-cone was selected and laid out as three plots to receive different treatment. Each was approximately the same shape and comprised 0.38 acre. Plot No. 1 was merely diked on the ends and sides so as to confine the water to a definite area. The native vegetation and top soil were in no way disturbed. The vegetation consisted of wild clover, wild oats, fox-tail, bermuda-grass, and a type of shrub known as "water-wally," with the wild oats predominating. On Plot No. 2 the vegetation was removed and the roots grubbed out. The soil was then cultivated so as to form shallow furrows about eight inches apart and parallel with the slope of the land. On Plot No. 3 the vegetation was removed, the land leveled, and banks constructed along the boundary so that a depth of water of from six to eight inches could be maintained on the Plot. Because the slope of the land in this locality is three per cent, it was necessary to divide this Plot into four basins and terrace them in order to have the ground-surface level.

Each plot was equipped with a system of six- by eight-inch feeder-flumes so as to distribute the water evenly. The inflows were measured by means of rectangular weirs and the outflows with 90°, V-notched weirs. All weirs were equipped with water-stage recorders. During operation sufficient water was supplied to each plot so as to have some outflow at all times, thus insuring 100 per cent coverage. The difference between the outflow and inflow was, of course, the percolation plus evaporation- and transpiration-losses.

The vegetated plot and the cultivated plot were operated continuously and in comparison for two spreading-seasons averaging 105 days. All three plots were then operated simultaneously for two spreading-seasons averaging 87 days. During this entire time of operation, the rate of percolation on the plot containing native vegetation was consistently the higher, being approximately 300 per cent greater than that of the cultivated plot and 150 per cent greater than the denuded basined plot. It should be noted also that the denuded plot had to be shut off for short periods and the surface treated in order to maintain a consistent rate of percolation, while the vegetated plot maintained its high rate of percolation for weeks at a time.

As further evidence of the effect of vegetation on the rate of percolation, take another area where the basin-method was utilized in our study. This experiment was originally in a river-channel and covered an area of about two and one-half acres. The water flowing over the outlet weir--and which was water refused by the denuded plot--spilled into a basin covered with a luxuriant growth of native weeds. The area covered in this weed-plot with the measured amount of water running into it, reflected an even greater ratio of percolation-rates in favor of the vegetated plot than did the Azusa plots.

In order definitely to check our theory that plant-life is an influencing factor in percolation, we have recently sown a crop of barley and oats, both wild and tame, on the Azusa Area heretofore operated as a denuded plot. During the present season this plot is being operated in comparison with the plot on which there has always been a luxuriant growth of native vegetation. The records of this year will also be compared with those collected before plant-life was permitted to grow.

The question arises as to whether the difference in the indicated percolation on a vegetated area and a denuded area should be charged wholly to percolation, or whether an allowance should be made for consumptive use by the plant-life. Inspection of the records collected on the Azusa plots shows that the all-time average rate of percolation of the vegetated plot was 5.55 acre-feet per acre per day and on the denuded plot 3.84 acre-feet per acre per day, or a difference in the rate of percolation of 1.71 acre-feet per acre per day. It is estimated that the consumptive use by the vegetation is not over 0.3 acre-inch per acre per day during the spreading-season, and probably not over 0.2 acre-inch per acre per day greater than the evaporation from the free water-surface on the denuded plot. Comparing this figure with the 1.71 acre-feet difference in percolation-rate on the two plots, it would appear that from this point of view the use of vegetation on a spreading-area is warranted and the waste caused by the transpiration is far overbalanced by the increased percolation.

The greatest variation in percolation-rates was found on the denuded plot. They ranged from about eight acre-feet per acre per day to slightly over one acre-foot per acre per day. On this plot we found that the rate of percolation decreased with the continued application of water, whereas a more consistently high rate was recorded on the vegetated plot. The rate would decrease at a fairly uniform rate with the continued application of water and would reach a minimum in three or four weeks' run. It was found that the percolation could be increased to its original rate by removing the top one-half inch of soil covering, but that after doing so the rate would again drop with continued application of water.

Upon the suggestion of D. A. Lane, who utilizes this method on the City of Los Angeles Spreading-Grounds in Tujunga, the soil-surface of the ground was merely harrowed to break up the surface-crust. The same results were obtained by this procedure as when the top soil was removed. This indicates either a small mineral deposit or algal growth or the presence of both of which there was some evidence on the soil-surface; possibly there had been also a rearrangement of soil-particles resulting from the action of the percolating water. Why the same condition does not exist on the vegetated plot is thought to be explained by the root-action of the plants. After three years' operation the cultivated plot was discontinued because it fell so far behind in efficiency and because almost constant attention was required to maintain a fixed wetted area.

The next factor to be studied was the effect of a fluctuating water-table on the rate of percolation. Because the ground-water basin, known as Canyon Basin, in which the Azusa plots are located, is relatively small and the outflow is slow across or through the barrier which forms its lower boundary, it is possible to fill the basin completely by spreading. Measurements taken at a well in the basin show that the water-table fluctuates from about 130 feet below the ground-surface during the late summer to as high as two feet below it in the early spring.

In order to study the effect of this fluctuating water-table on rate of percolation, five observation-shafts were sunk in the vicinity of the experimental plots during the summer of 1932, when the water was at a low level. The shafts range from 12 to 30 feet in depth, and water-stage recorders are maintained in each throughout the spreading-season. Shaft No. 1 is located about 75 feet up the slope of the land from the plots; shaft No. 2 is about 15 feet south and east of the plots; and the remaining three are on a north-south line extending below the plots with the farthest being about 1300 feet distant.

Since the plots are near one edge of the ground-water basin, the movement of the water-table within certain limits can be partially controlled by the spreading in the basin. This is accomplished by varying the amounts of water diverted to the large spreading-area lying directly west of the plots. An increase or decrease of the amount diverted is reflected by a rise or lowering, respectively, of the water-table. It was also found that by spreading a large amount of water along the edge of the ground-basin on which the plots are located the water-table could be brought within a few feet of the ground-surface. Our records indicate that there was no appreciable decrease in the rate of percolation until the water-table came in actual contact with the ground-surface. When this contact was made the percolation-rate on the vegetated plot decreased from about five acre-feet per acre per day to a little over three acre-feet per acre per day, with smaller decreases being recorded on the other two plots. At this time the general plane of the water-table surrounding the plots stood about five feet below the ground-surface, but immediately under the plots a mound of water five feet in height had been formed by the percolating water. During these periods of extremely high water-table the rate of percolation on all three plots tended to become stable, indicating that the factor controlling the percolation was no longer at the ground-surface but that the rate was then dependent on the lateral movement of the water which formed the mound.

The height of the mound built up under spreading-areas will probably vary considerably with different soil-types and underground conditions. A very porous soil will permit the mound to spread over a greater area and the underground water-movement will be faster than with a tighter soil. The method used in spreading will also influence to some extent the height of the mound, as those methods producing the greatest percolation-rates will allow the largest quantities of water to pass underground in given times to form the mounds.

When the spreading on the adjacent lands was decreased to less than the amount of water escaping from the underground basin, the water-level lowered and the relatively small amount percolating through the experimental plots was not sufficient to maintain an elevated water-table. Rates as high as two feet per hour were recorded in the water-level drop. During these periods the percolation-rates on all three plots were at a maximum. The theory has been advanced that a partial vacuum was formed between the falling water-table and the saturated ground-surface of the plots, thus resulting in the higher percolation-rates. If this were true we would expect a reversed effect with a rising water-table due to confined air. This was not detected at the Azusa plots; but it should be mentioned that there the water-table rose at a much slower rate than it fell, and perhaps the rate of rise was not greater than the rate at which the soil-air could escape around the plots. A considerable number of what we thought were air-bubbles were noted at various times on the ground-surface of the plots during certain periods of spreading, but no relation could be detected between their occurrence and changes in percolation-rates.

Dr. W. L. Powers, Soil Scientist, Oregon Agricultural Experiment Station, has demonstrated the effect of confined air on the movement of soil-water, by means of soil-filled tubes. The results of these experiments (J. Agric. Res., December 15, 1934) show that under certain conditions confined air may have considerable influence on the rate of percolation. The greatest effect would, of course, be at the beginning of the application of water; after the soil-air has once been displaced by the percolating water we would expect no further influence from this source throughout the period of spreading.

The next factor to be considered is that of temperature. Continuous records of both air- and water-temperatures were collected during the entire period of operation of the Azusa plots. The temperature of the water was recorded on a distance thermograph with the bulb set on the ground-surface and completely submerged in the water at about the center of the vegetated plot. Air-temperatures were recorded on a thermograph set in a standard instrument-shelter near one edge of the plot.

The difference in the rates of percolation between two or more days was not noticed because of the small difference in the mean daily water-temperatures. During a 24-hour period, however, the mean hourly water-temperature often varied from 15° to 20° F, and a small temperature-effect was detected. To evaluate this effect accurately, the evaporation- and transpiration-losses would have to be known and a correction applied for storage-changes caused by a fluctuating outflow. As both items were based on estimates, no definite figure is set for temperature-effect. Sufficient data were obtained, however, to show that temperature had only small influence on the percolation, although where spreading is carried on under extreme temperatures this factor may require more serious consideration.

One other factor to be considered is the effect of silt. No data were obtained on this at the experimental plots because only relatively clear water was available for spreading-purposes. The effect has been noted on other areas, however, and is known to be highly detrimental to percolation. The writer has observed water standing in a shallow depression for two weeks after the application. The depression had originally been in a highly porous area, but approximately three to four inches of silt had been carried in by the water during diversion of a flood-flow and had practically stopped percolation. Generally, spreading-grounds to which it is intended to divert stream-flow have been designed with at least some provision for handling the silt. This may be either by a series of basins to act as settling-ponds or by the use of the ditch-method in the spreading-system with sufficient slope to maintain a carrying velocity.

The results of the above-mentioned studies are now being prepared for publication, together with a general review of the entire water-spreading program in southern California.

The author wishes to take this opportunity to thank those men who have so freely given information concerning the water-spreading grounds with which they are connected.

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REMARKS ON WATER-SPREADING

A. L. Sonderegger

This paper will discuss some of the problems which present themselves in the spreading of flood-waters. To those who have devoted some study to the mechanics of spreading, it soon becomes apparent that no two cases of spreading are alike, but that each has its own characteristics. This is not surprising for the simple reason that permeability, upon which the success of spreading naturally depends, is a combination of a number of contributing elements. There is the mechanical, mineral, and chemical composition of the spreading constituents of the spreading-grounds; the character of the vegetal cover; the depth to the water-table; the gradient of the terrain, and finally, the percentage and composition (mechanical, chemical, and mineral) of the bed-load, silt, and colloids.

Some of the factors here enumerated, relative to the absorptive materials, depend upon the composition of the rock-masses from which the materials were eroded. They also depend upon the distance to which the materials have been carried, the force of the stream, and the peculiar action of the flood-waters which caused their transposition and deposition, for the manner in which debris has been laid down determines also the line of least resistance to percolation.

Such conclusion is supported by the well-known phenomenon of interconal resistance to the percolation of water, which may effectively prevent the mingling of ground-waters between cones built up with debris originating in adjacent and kindred watersheds.

Having further in mind that of all moving bodies water has the ability to adapt itself most perfectly to follow the line of least resistance, responding readily to seemingly negligible influences, it is not to be wondered that the spreading-practice, which has developed in one locality, will not bring equally good results in another, and that in each instance considerable study and experimentation will be required to attain the best.

In cases where regulation by storage produces a practically clear effluent, or where diversions are restricted to the normal flow in winter, the problem of spreading resolves itself into one of application of mechanical principles which are well known and need not be discussed here.

A matter of general interest is the effect of vegetation on the rate of percolation. In the experiments of the Division of Agricultural Engineering of the Department of Agriculture, which were made on the San Gabriel Wash in southern California, it has been proven, for instance, that the natural vegetal cover, consisting of wild clover, wild oats, fox-tail, Bermuda grass, and water-wally shrub, produced a higher rate than furrowed or cultivated ground. It is believed that a vegetal cover has the beneficial effect of breaking up the surface-soil, thus making it more amenable to absorption.

The spreading-basins on the Santa Clara River in Ventura County, described by V. M. Freeman, have been left in their natural state of vegetal growth, apparently to take advantage of this condition.

On the other hand, the experiments made by D. A. Lane, Engineer in charge of the Tujunga Spreading-Grounds of the City of Los Angeles in San Fernando Valley, have led to the conclusion that a maximum rate of absorption in basins could be maintained by periodical cultivation (J. Amer. Water-Works Assoc., v. 26, No. 4, 1934).

A gross area of 80 acres was purchased for spreading. The maximum flow spread in 1932-33 was 106 second-feet on 47 acres. In 1934-35, a mean daily flow of 54.85 second-feet of Owens River water was absorbed on an area averaging 17.43 acres. The average unit-rate of percolation for the 221-day spreading-period was 6.24 acre-feet per acre per day.

Seasonal average unit-rates and percolation, since the beginning of spreading-operations in 1931, in acre-feet have been as follows: 1931-32, 6.15; 1932-33, 6.92; 1933-34, 5.51; 1934-35, 6.24. The average was 6.205 acre-feet per acre for the four seasons. With muddy water, absorption was at the rate of five acre-feet per acre per day.

These percolation-rates are as high, if not higher than any accomplished on a large scale, under continuous operation and with a relatively small area. Cultivating of beds is done at intervals of ten to fourteen days, depending upon weather-conditions.

Another problem not so readily solved, however, presents itself in the spreading of muddy water, diverted from streams in flood-flow. Desilting-basins have been used in many cases, but require continuous maintenance. Mr. Freeman has stated that in the Santa Clara River Works no flood-waters containing more than 20 cubic feet of silt per acre-foot will be diverted into the spreading-basins because of clogging. Muddy water and vegetal growth is a combination that is not workable with basins. To cause the absorption of silty water requires water in motion. We know that silt-laden sheet-water flowing over debris-cones percolates into the gravels, particularly when the wash is grown up to brush. The practical application of such practice, however, is, in many cases, not feasible because of the hazard arising from possible loss of control of the diverted flood-water. It is equally well known that channels absorb water from muddy streams, provided velocities are critical or scouring. The rate of seepage under such conditions may prove to be low, yet this method applied to spreading-ditches may offer the only feasible solution.

From the practical standpoint, the problem apparently lies in regulation of the spread-water to possible lowest non-silting velocities, which, in turn, for any given area, will permit construction of ditches of minimum gradient and hence of greatest length.

Muddy flood-water naturally will carry a bed-load of silt, sand and gravel, and a load of solids in suspension. Since critical velocities generally become greater in proportion to the volume of bed-load, and therefore require increasingly steeper gradients, the first important step will be the trapping of the materials in traction.

Depending upon the degree of success of this operation, there remains, then, a muddy water which, under ideal conditions, will consist of a load of suspended materials and colloids, which must be carried the full length of the ditch. However, it is to be expected that there will always be some silt bed-load and that the critical velocity will depend upon the character of the silt in traction rather than upon that in suspension.

That critical velocities, even under these favorable conditions, vary within wide limits, has recently been discussed in a paper entitled "Stable channels in erodible materials" by Professor E. W. Lane of the State University of Iowa (Proc. Amer. Soc. C. E., November 1935). It is noted that critical velocities, determined for 26 silt-laden streams in Indian, Egyptian, and Imperial Valley canals, vary for one foot depth of water from 0.4 foot to nearly two feet. This is a remarkably wide range. If analyzed on the basis of Kennedy's formula, which is critical velocity V_0 = C (coefficient) times depth d^n, it becomes apparent that for $d = 1$ the value of V_0 depends entirely upon the coefficient C, that is, a quantity independent of the shape of the canal but stated by Kennedy as varying with the quality and quantity of silt. The quality of the silt and of the colloids is apparently important; in fact, C and especially V_0, seem to be factors which, like permeability, depend not only upon mechanical properties, but upon the combination of the mechanical and chemical properties of the silt, as well as the materials composing the bottom and sides of the channel. The evaluation of the various components affecting the V_0 of a stream in flood-flow is, therefore, far from being simple.

However, a fair idea of the mineralogical nature of the debris composing the cone and of the suspended load may be obtained from a study of the mineral composition of the tributary watershed, whether igneous, metamorphic, or sedimentary. For example, if granitic, the composition of the granite should receive attention, particularly the feldspar-component, whether orthoclase, which breaks down into an aluminum silicate tending to produce clayey residuum, or plagioclase (as in certain diorites), which decompose into silts.

A careful study of the geology of the watershed will thus give some idea of the relative proportion of clay- and silt-materials and the tendency to produce colloids which, because of their cementing characteristics, have a detrimental effect on percolation.

The application of the foregoing analysis to spreading-ditches resolves itself into a regulation of the flow of muddy water to critical velocities by means of undershot checks. Such checks are found in most irrigation-canal systems and are effective in regulating the velocity without the accumulation of silt. The silt-load will naturally vary with the flood-stage and provision for adjustment of gradients, as permitted by such checks, is therefore a requisite. The wide fluctuations in measured critical velocities, as shown by Lane, make estimates so conjectural as to be of but little value, and means of regulation must be provided.

Spreading-ditches, to be operated along the principles here outlined, are being constructed on the Santa Ana Cone in southern California by the Water-Conservation Association which was organized many years ago by water-users in Riverside, San Bernardino, and Orange counties. A few years ago, the Association constructed a weir at the mouth of the canyon of the Santa Ana River, which permits the diversion of flood-waters at all stages of a flood. It controls about 2700 acres of spreading-grounds on the Santa Ana Cone and, with the help of Civilian Conservation Corps and other labor, of late years has constructed many miles of ditches for the conveyance and absorption of muddy water. Provision is made for the flushing of these canals, at convenient points, into the River or its tributary, Plunge Creek. Because of the preponderance of large boulders, permeability on this Cone is relatively low and at times in the past was impaired by silting of the spreading-ponds. It is expected that the new system of ditches will permit diversions during the first days of the flood when the water is very muddy and carries considerable quantities of debris in traction.

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PERCOLATION FROM SURFACE-STREAMS

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The underground basins which supply much of the water for human consumption are replenished by rain-water, irrigation-water, underground streams or percolation from surface-streams, or a combination of these. Surface-streams include not only rivers and streams, but also unlined canals. In most cases the percolation from surface-streams is the major contributor to the underground basin and in the Salt River Valley in Arizona field-measurements have shown that the surface-streams, including a network of irrigation-canals, contribute approximately 75 per cent of the water received by the basin underlying the Valley. These field-measurements, as well as field-work done elsewhere, yielded only quantitative results for isolated cases and no knowledge was acquired concerning the manner or path in which the water travels from the surface-stream to the underground basin.

In 1931-32, experiments were conducted at the California Institute of Technology to investigate this phenomenon qualitatively. To reproduce the condition of a stream flowing down the center of a large valley, a wooden tank nine feet long, four feet high, and three feet wide with a paneled glass front was constructed and filled with sand of known characteristics. This represented a transverse slice of the valley and the stream-bed was simulated by a bottomless tank set on top of the sand, into which water was sprayed at a known rate. Initially, the variable discharge outlets at either end were set at the same elevation creating a level water-plane with the stream in the center of the cross-section. In order to determine the path (and particularly the outline) of the water in traveling from the surface-stream to the underground water-plane, a solution of household bluing was admitted to the river-channel. Extended investigation of dyes led to the use of the bluing because of its visibility and economy. The dye showed that when the water first started percolating from the stream, it trickled downward beneath the stream-bed in a vertical column, with little or no lateral movement, indicating zero-pressure within the column. This condition was termed "free-fall." Upon reaching the ground-water plane, the water began building a "ground-water ridge" (a hump in cross-section) which rose as the flow continued until, in most cases, it reached the stream-bed. At this point the flow-condition changed, the water flowing laterally as well as downward immediately beneath the stream-bed. This condition was termed "pressure-flow," since the water was under pressure as evidenced by the lateral movement.

To determine the path of the water within the "ground-water ridge," the "flow-net" for the section was constructed from the piezometer-readings within the sand. The "flow-net" consists of two families of orthogonal curves, one "equi-pressure" lines, the other, flow-lines. It was found, as was to be expected from the symmetry, that the quantity discharged at either end was the same. The flow-lines showed that the water is moving in the whole area available for discharge, there being only a small triangle of dead water directly below the surface-stream at the impervious bottom.

Then an unsymmetrical condition, such as a stream flowing along one side of a valley near rock-walls, was reproduced by closing one outlet while leaving the other open. Again the "flow-net" was constructed and it was found that the water spread laterally in both directions on leaving the stream-bed, the water spreading out to include a large area of cross-section for percolation as in the other case. On the side with the closed outlet the path of the water reversed its lateral movement about half way down to the bottom and swung around toward the open end. The path nearest the open end followed a conventional curve to the outlet. It was also observed that the water-table between the stream and the closed side was maintained at an elevation considerably above the elevation of the outlet on the other side.

Other cases of dissymmetry gave results which were consistent with work outlined above. With equal outlet-elevations and the stream-channel nearer one outlet, the greater discharge was at the closer side. With the tank in the center and unequal outlet-heights, corresponding to a water-table tipped laterally, the greater discharge was at the low outlet.

This work was carried out with just one type of sand so that the qualitative results were typical of any uniform material, but the quantitative measurements were only relative. The condition of "pressure-flow" was established and the discharge was found to be a function of the total head, measured from the water-surface in the stream to the ground-water table at a considerable distance from the stream. Most of the head-loss is due to friction within the sand and a small part is the entrance-head loss in getting the water into the sand. This latter is similar to a screen of considerable thickness along the axis of the openings. The condition of "free-fall" was defined and found to be a temporary or unusual condition in which the discharge was governed by entrance-head loss alone and therefore the depth of the water in the stream. In all cases the area for discharge of water through the sand as limited by an impervious stratum is of primary importance, although it will not be a controlling factor in "free-fall."

In order to elaborate the results of the qualitative investigation, a quantitative study was made on three different sands. The apparatus consisted of a double-walled cylinder with controlled outlets, in which the sand was placed in the inner tank and water run through the column of sand. It was arranged so that the length of the sand-column could be varied from five to 15 feet, the depth of water over the sand from a few inches to 15 feet, and total head from zero to 20 feet.

From this work it was found that the head-loss was due to three factors: Transmission, entrance (and exit), and capillarity. The first was the major element, the other two being minor but real losses. A formula was developed to express this head-loss in the form of the three elements, but would require additional work on more types of sand to verify the factors relating to sand-characteristics. In establishing this formula, difficulty was encountered in using any of the standard effective size-of-particle definitions, and led to the use of an empirical sand-area factor. This was a verification of King's aspirator-method in which air is blown through the sample of sand to determine its resistance, since the resistance would include the effect of a large or small surface-area as well as openings or voids. The transmission-loss was found to be a function of the sand-surface area, voids, velocity, area of section, and temperature. Slichter's work was examined and found to agree basically with the experimental results obtained here. It was found, however, that there is no relation between Slichter's mean effective diameter and Hazen's mean effective size and the latter should never be used in Slichter's formula.

The magnitude of the transmission-loss factor as determined by these experiments accounts for the prevalence of the "pressure-flow" conditions in the field, since the ground-water ridge must rise to a height equivalent to the transmission-head loss and this being large usually requires that the ridge rise to the limit or the water-surface in the stream, establishing "pressure-flow."

These experiments have shown the manner in which water percolates from a stream-bed to the underground basin and established "pressure-flow" as the general case in which the quantity is the function of the total head measured from the surface of the water in the stream to the ground-water plane at some distance from the stream. The condition of "free-fall" has been demonstrated as an initial or temporary condition, except in particular cases, and the quantity is a function of the depth of the water in the stream. The importance of the surface-area in the head-loss factor has been established. In the practical case the quantity is best determined by one field-measurement and from this the quantity under other conditions can be estimated quite accurately. Lacking field-data, King's aspirator-measurement on a sample will give the best sand-constants, or the formula can be applied, but the results from the formula are questionable until further work in this field is done.

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MOVEMENT OF GROUND-WATER

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(Abstract)

The movement of water through formations having capillary openings is generally laminar and obeys Darcy's law, at least down to very low gradients. About 1000 samples tested in the laboratory of the United States Geological Survey have coefficients of permeability ranging from 0.001 to 90,000, indicating probable velocities ranging from a fraction of a foot to a few miles in a year. The Thiem field-method gives promising results for determining permeability. Movement through sub-capillary openings is important but poorly understood; molecular attraction of the water offers great resistance to movement or compression.

Water in rocks tends to move from positions of high to low pressure, both along and across the strata. Pressure-changes are transmitted with much lag under water-table conditions and less lag under artesian conditions, according to the transfer of water involved. With respect to development of cones of depression, oil-wells somewhat resemble water-table wells. Essen-

tially static conditions of water or oil may be found in underground reservoirs that are completely sealed or sealed at one end or that contain fluids that differ in specific gravity, as water and oil, or fresh and salt water.

[Note: A digest of the paper was given which was presented at the meeting of the American Association of Petroleum Geologists in Dallas, Texas, March 23, 1934, to be published in the Bulletin of that Association for June 1936.]

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GENERAL DISCUSSION

Harold Conkling

The general subject of the papers to be discussed has been contributions to ground-water. Deep penetration of rainfall and percolation from streams are natural supplies while spreading of surface-streams is an induced supply. Percolation from streams is measurable but occasionally at great expense because of the large flashy flows which occur in such streams as the coastal streams of California. Deep penetration from rainfall is not directly measurable but, in the field and laboratory, runoff can be measured and also the water retained in the root-zone (consumptive use) and that evaporated, leaving deep percolation as the residual in the equation. The runoff from an area may flow into a stream-channel and there percolate but in the calculation this additional percolation is neglected. Likewise, as is evident to any observer, the surface of the ground is uneven and rainfall concentrates in the depressions whether small or large. As deep percolation is not proportionate to the rainfall but is a much larger percentage of a 10-inch rainfall, say, than from a rainfall of five inches, beneath the depressions it will be much greater than beneath the hummocks and the result will be a greater overall deep penetration than that calculated from observations on a smooth piece of ground. This fact, together with the fact that percolation occurs from streams formed by runoff of the rain on the valley-floor, tends to make actual percolation from precipitation greater than calculated from field-observations. No suggestions are made as to methods of observation to overcome these difficulties. If none can be found, it is presumable that experience will ultimately reveal approximate factors to apply to observed results. If there is error, it appears to be always on the minus side.

The estimated contribution of deep percolation from rainfall to underground supplies by the foregoing method can be checked indirectly by another method. This involves an accounting of all water on an area, that is, the stream-discharge to it and rain on it and the stream-discharge from it together with an evaluation of storage-change in the underground basin. San Gabriel Valley in southern California is physically favorable to such determination and data for the past 12 years are extraordinarily complete. Possibility of error lies in evaluation of change in underground storage.

Evaluations of deep penetration of rainfall by this method are approximate since it is a by-product arrived at after several assumptions. By this method, rainfall-penetration appears to be considerably larger in San Gabriel Valley than by the method just described--more than could reasonably be accounted for by errors in assumptions.

It is not improbable that the future will give a method of reconciling these apparently discrepant results. The discrepancies are noted here to call attention to the difficulties in accurately evaluating contributions to underground supplies when rainfall constitutes a considerable portion of the supply.

Spreading--There should be an investigation of the economics of spreading. The benefits are two: Conservation by storage underground and decrease in cost of pumping due to raised water-table.

In the South Coastal Basin loss of water into the ocean from the mountain is about one-sixth the mountain-discharge in the long-time average. Loss of valley-floor rainfall into the ocean is a much larger amount than loss of mountain-water in the dry years. If all the mountain-discharge were spread and thus conserved, it would probably not increase the underground supply ten per cent. Most of the waste into the ocean from the mountains occurs in years of heavy discharge, in which years only a very small percentage can be spread without reservoirs to equate the flow so that probably the actual increase which could be secured by maximum spreading possible without reservoirs is almost a negligible percentage. Reservoirs of considerable magnitude to control floods are necessary.

This is true of South Coastal Basin where the valleys slope steeply but is not true of some parts of the valleys of Ventura County and a great deal of Santa Clara Valley (Santa Clara County). In the vicinity of Saticoy in Ventura County and in Santa Clara Valley (Santa Clara County) the terrain is fairly flat and the ground porous in the areas where spreading is proposed. In these areas spreading-works of considerable magnitude seem to fully justify themselves.

Spreading is done in the San Joaquin Valley from Kings River inclusive south and to an extent north of Kings River. However, it is not called spreading. The farmers merely irrigate at all times when water is available. It was not done at first to raise the water-table, but such was the result and now the storage underground and consequent rise in water-table is regarded as one of the benefits of out-of-season irrigation. In Santa Clara County irrigation has been practiced at all times the flashy streams flowed water. Most of the net result was deep percolation and storage of water underground. Some of the works proposed or in process in that Valley merely utilize the old canals and improve on past methods. Spreading is merely irrigation for the direct purpose of inducing percolation.

Data published as to amount of water-spread in different works now installed are misleading. In two cases at least the amount of water which is spread would have percolated anyway, in part lower down on the stream. The net addition to the underground supply is intangible, being only that part which may be saved because by spreading it is induced to percolate higher up in the valley and thus prolong the time it is underground, making it available for pumping a longer time before it reaches the ocean. In other cases, whatever the amount of net spreading, the net addition to the underground supply over a long term of years is nothing because the underground basin is kept more full in the dry years with the result that it is filled more quickly in wet years with greater consequent waste in those years.

Aside from conservation which spreading-works may bring about, they may benefit the water-user by raising the water-table in a particular area during a dry cycle. If the voids in the alluvium be assumed at 15 per cent, an acre-foot of water if it could be confined under a particular acre would raise the water-table seven feet. Quoting from "Irrigation-practice and engineering" by Etcheverry and Harding, the cost of pumping one acre-foot in central California with a seasonal pumping of 300 acre-feet and a pump-capacity of 450 gallons per minute is $1.55 per acre-foot for a 20-foot lift and $4.35 per acre-foot for a 100-foot lift, a decrease of $2.80 per acre-foot with an 80-foot raise in water-table. At 15 per cent voids it would take 11.4 acre-feet to raise the water-table 80 feet. At 20 cents per acre-foot for spreading, the cost of spreading would be $2.28 as against $2.80 saved in pumping cost. The $2.80 saving must be discounted because not all the 11.4 acre-feet will remain available in any one locality and the part lost to that locality may not benefit another. Thus this benefit may be less than generally given credit for.

It is evident that there should be a very critical examination of economics before spreading-works are installed just as there should be and generally is a critical examination of economics before a reservoir is built. In general, spreading-works cannot take care of all the water of a large flood but there are exceptions where stream-beds are extensive and the water does not need to be taken from them. In general, lay of the land and percolating capacity in southern California streams are more favorable to spreading a considerable distance below the stream-cones found at the mountain-toe, but on the other hand land in these lower locations is more costly and danger in taking the stream out is much greater. Spreading is most often successful with reservoirs to control the peaks and de-silt the stream. Where mountain-reservoirs are too costly, they may be built on the cones, but if the slope is steep they are in many cases unjustified. And by the same token spreading itself would be unjustified from the viewpoint of the basin as a whole. In many cases spreading-benefits appear to be purely local, and if only small works are attempted it can be done at slight cost. No general statement can be made. In some cases spreading is the only method of conservation which appears feasible and no surface-reservoirs are necessary to make it so.

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PAPERS

BASIC HYDROLOGIC DATA

Donald M. Baker

The lack of adequate hydrologic data has probably been the underlying cause of more loss of life and money through failures of engineering structures and enterprises than any other factor, and we are daily paying large sums because of this lack of data.

The dam which fails because it was over-topped by a flood had inadequate spillway-capacity, and this probably was due to the fact that the designer did not have sufficient rainfall and stream-flow records. The irrigation-district whose crops are left to die during a drought because of lack of water-supply can place the blame largely upon inadequate hydrologic data when the project was planned. The farmers who plowed up and planted the western plains during periods of ample rainfall and then saw their crops burnt up or buried in dust when a dry period came along might not have been so enthusiastic had ample precipitation-records been available to show them that these recurring drought-periods could be expected in that region.

Here in southern California we have wide extremes in the occurrence of hydrologic phenomena. Our precipitation may range from 30 per cent to 250 per cent of normal, while our stream-flow may vary from below ten per cent to 700 per cent of normal. The largest floods of which we have knowledge--those of 1884 and 1889--occurred when the region was still on the frontier, and no records exist as to their magnitude except old men's stories. One wonders how much is being spent in over-design of hydraulic structures because of lack of these flood-data.

Again, the safe yield of most of our water-supplies for domestic use and irrigation-purposes is based on the famous 9-year drought which occurred from 1896 to 1904, inclusive. One finds, if he goes back to the original source, that the few records of stream-flow which existed during that period, are little more than intelligent guesses--maybe from 25 per cent to 100 per cent one way or the other of the actual quantity occurring. Again, one wonders if the safe yields established for most of our water-systems are too high or too low.

It is impossible to cure this lack of data in the past. Last year's rainfall or stream-flow can only be obtained last year--the clock cannot be turned backwards--but an adequate program for the collection, compilation, and publication of these data in the future would not be costly and would pay several thousand-fold upon the investment.

Before studies can be made on projects involving either the regulation or the utilization of water, or before plans can be drawn for structures, basic hydrologic data must be available. These data may be defined as records of measurements and observations of the quantity per unit of time of: Precipitation, including snowfall; stream-flow; evaporation from water; quality of water, materials either in solution or in suspension; the elevation of natural water-planes, both surface and underground, and the change thereof from time to time; and of such other related phenomena and natural conditions as are necessary to allow estimates of past, present, and probable future occurrence of water to be made. The unit of time involved in recording the quantities may vary from seconds to years, and depends upon custom, convenience, and method of compilation and publication of the data.

The basis for use of hydrologic data in planning projects for water-utilization and regulation rests upon the assumption that climatologic and hydrologic conditions which have occurred in the past will occur in a somewhat similar manner in the future, and therefore a record of past occurrences of precipitation, stream-flow, runoff, water-quality, et cetera, if of sufficient duration, may be taken with reasonable assurance as a forecast of future occurrences.

In the same manner, engineering data concerning properties and behavior of materials of construction are utilized in planning and making designs for engineering structures, and predicting the performance of same under varying conditions of service and operation. These data, however, differ in their nature from hydrologic data.

The physical properties and behavior of construction-materials may be tested in the laboratory and checked by use of models in a relatively short time and at small expense, and, from such tests, proper safety-factors determined for use in design and construction.

Coming to the planning of water-projects, if factors of safety comparable to those used in engineering structures were taken in estimates of water-quantity, many of our water-supplies would remain undeveloped because of inadequacy of the estimated supply or the high resulting cost of structures necessary to utilize or regulate the water. A bridge may be built strong enough to carry four times the load that will ever be placed upon it, but a reservoir four times the size required for adequate regulation is never built. We cannot say that a watershed has a safe yield of 500 acre-feet per square mile, apply a safety-factor of four, and only develop 125 acre-feet per square mile, nor can we say that a stream will have a maximum expected flood-flow of 100,000 second-feet with a frequency of once in 100 years and design a spillway for 400,000 second-feet. Either would be uneconomic. In fact, in too many cases the factor of safety used is entirely too low in view of the quality and amount of hydrologic data available, and since extreme conditions of regimen, either maximum or minimum, only occur at infrequent intervals, the resulting inadequacy is not experienced until long after the structure is built.

Due to the great variations in climatological phenomena, the time- and place-factors in hydrologic data are of paramount importance. Precipitation, stream-flow, unit-runoff, and quality of water differ greatly from day to day, week to week, month to month, year to year, and even over longer periods at given locations, and they also vary in an abrupt manner from place to place, particularly in sections of rough topography.

Furthermore, man cannot control the amount of precipitation falling upon a given watershed or the flow of water in a stream, as he can the strength of steel or concrete. Neither can he accelerate the collection of hydrologic data in the same manner as he can the determination of information relative to construction-materials or theories of design.

While it is possible, given a record of precipitation, stream-flow, or annual runoff with their intensity or magnitude, by use of the laws of probability to obtain a reasonable estimate of the magnitude of variation of these phenomena and of their frequency of occurrence, such records must be of considerable length for resulting information to be of any great value.

Precipitation or stream-flow at one place cannot be estimated from records obtained at another location, unless a very considerable amount of similar data is available at adjacent places, and then the accuracy of the resulting estimate will depend largely upon the amount of data at such adjacent locations, the proximity of these locations to the place in question, and the degree of similarity in climatic conditions between the locations compared.

Since projects for water-utilization or regulation cannot in general await the long period necessary for the collection of adequate hydrologic data, two things are necessary: First, that a fairly complete network of observation-stations for the collection of hydrologic data be established throughout the country, with a concentration of such stations in the regions where prospective development is contemplated, at a sufficient time prior to probable development to obtain a record of adequate length; second, that the fullest information regarding all existing data, both as to their details and as to their quality, be available in convenient form so that when plans are being considered for a water-project there will be available the largest amount of data possible, with ample information available regarding their quality, in order that a proper factor of safety may be applied in their use.

There are two common viewpoints regarding quantity and quality of these data, that of the collecting agency and that of the user. These are well illustrated by the remark of the irrigation-engineer who said he would rather have a dozen precipitation-stations of 15 to 20 years' length each upon a watershed, even if the gages consisted of tomato cans, than one record of the same length taken with an automatic recorder. The collector is primarily interested in quality and accuracy of record, while the quantity and length of records appeal to the user. Somewhere in between these two viewpoints a happy medium must be obtained. A poor record is far better than no record, and will not be misleading if full information as to its quality is available, since then a proper safety-factor may be applied to the result.

At present the Federal Government is the largest collector and publisher of basic hydrologic data. Th type of data collected and the Federal agency now principally engaged in the collection of each type of data, with the total number of observation-stations is shown in Table 1. While this Table indicates that the Weather Bureau and Geological Survey are the most active Federal agencies in the collection of basic hydrologic data, a total of 33 agencies collect one or more kinds of data as shown by Table 2. A great deal of this work is carried on upon a cooperative basis, funds being supplied to the Federal agency by States or local bodies. While it might appear at first glance that this wide distribution in the collection of data among so many agencies indicates a high degree of duplication and a dispersion of energy, such is not entirely

Table 1--Type of basic hydrologic data collected by Federal agencies

Type of observations	Principal agency engaged in collection of data	Total No. observation-stations[a]
Rain-gages, standard and recorded	Weather Bureau	6123
Snow-boards	Weather Bureau	815
Snow-courses	Bureau of Agricultural Engineering	512
Stream-gages	Geological Survey	4685
Ground-water observation-wells	Geological Survey	6659
Evaporation, first-order and simple	Weather Bureau	136
Silt-observations	Soil Conservation Service	154[b]
Chemical analyses of water	Geological Survey	25[b]

[a] Probably incomplete.

[b] These numbers are based on reports submitted by Federal agencies to the Water-Resources Committee; the totals have not been checked fully and are therefore subject to revision.

Table 2--Federal agencies engaged in collection of basic hydrologic data

Agency	Type of observations							
	Rainfall	Snow-fall boards	Snow-course surveys	Evaporation	Stream-gaging and stage records	Ground water observations	Water quality	
							Silt	Chemical analysis
Total number stations operated[b]	6123	815	512	136	4685	6659	154[a]	25
1 - Aeronautics, Bureau of	X	..	..	..	..	..	..	..
2 - Army, U.S., miscellaneous	X	..	..	..	..	..	..	..
3 - Biological Survey	X	..	..	..	..	..	..	..
4 - Agricultural Engineering, Bureau of	X	..	X	X	..	X	X	..
5 - Civilian Conservation Corps	X	..	..	..	..	..	..	..
6 - Coast and Geodetic Survey	X	..	..	..	..	..	..	..
7 - Coast Guard Service	X	..	..	..	..	..	..	..
8 - Commerce, Dept. of, miscellaneous	X	..	..	..	..	..	..	..
9 - Customs Service	X	..	..	..	..	..	..	..
10 - Engineer Corps, U.S. Army	X	..	X	X	X	X	X	X
11 - Entomological Laboratory	X	..	..	..	..	..	..	..
12 - Fisheries, Bureau of	X	..	..	..	..	..	..	..
13 - Forest Service	X	X	X	X	X	X	X	..
14 - Geological Survey	X	..	X	X	X	X	X	X
15 - Health Dept., District of Columbia	..	..	..	..	..	..	..	X
16 - Hospital, U.S.	X	..	..	..	..	..	..	..
17 - Immigration Service	X	..	..	..	..	..	..	..
18 - Indian Affairs, Bureau of	X	..	..	X	X	..	..	..
19 - International Boundary Commission	X	..	..	..	X	..	X	X
20 - International Joint Commission	..	..	..	..	X	..	..	..
21 - Lighthouses, Bureau of	X	..	..	..	..	..	..	..
22 - Navy, U.S.	X	..	..	..	..	..	..	..
23 - Park Service, National	X	X	X	..	X	X	X	X
24 - Plant Industry, Bureau of	X	..	..	X	..	X	X	X
25 - Post Office Department	X	..	..	..	..	..	..	..
26 - Public Health Service	..	..	..	..	..	..	..	X
27 - Quarantine Service	X	..	..	..	..	..	..	..
28 - Reclamation, Bureau of	X	..	X	X	X	X	X	X
29 - Sanatarium, U.S.	X	..	..	..	..	..	..	..
30 - Signal Corps, U.S. Army	X	..	..	..	..	..	..	..
31 - Soil Conservation Service	X	..	..	X	X	X	X	..
32 - Tennessee Valley Authority	X	..	..	X	X	..	X	..
33 - Weather Bureau	X	X	X	X	X	..		..
Number of agencies operating stations	30	3	7	10	11	8	10	8

[a] Incomplete figures.

[b] These numbers are tentative and subject to revision.

the case. It is largely a matter of convenience or availability of funds. Many instances occur where one Federal department will, for purposes of economy, make available funds to another agency which can collect the data in a more economic manner. To the user of this data it makes little difference by whom it is collected, so long as such collection follows standardized procedure, and so long as all data of any particular kind is published by a single agency.

The Committee on Standards and Specifications for Hydrologic Data, set up by the Water-Resources Section of the National Resources Committee last year, issued a report in November 1935, covering standards of collection, form, and agency of publication of these data, and much progress has been made toward putting its recommendations into effect.

The following discussion covering the various types of data collected by Federal agencies represents the writer's view from the standpoint of a user of these data as to their adequacy and their methods of publication, and is based in part on recent work by the Committee on Standards and Specifications. The Committee is now completing a report on "Deficiencies in basic hydrologic data."

Precipitation--Of the 6123 rain-gages operated by Federal agencies, 4947 are operated by the Weather Bureau, and 174 of the latter are recording-gages at first- or second-order stations, the remainder being standard 8-inch gages operated by cooperative observers who in most cases receive no compensation.

In the settled sections of the country a fair distribution of standard rain-gages exists--in fact, some localities have too many--but in the unsettled areas, and particularly in the higher mountainous regions which produce most of the water-supply, there is a lack of gages. Also many old records exist which have been discontinued and which should be revived because of the great value attaching to length of record.

Much has been done during the last year or so to place gages on ground-level instead of upon high buildings, many of the records obtained upon high buildings being misleading.

A great deficiency exists in the number of recording-gages throughout the country, several times the present number of gages being needed. A great many private records of rainfall exist, some of them of considerable length, which should be published. There is a very great need for the compilation and publication of complete histories and description of all stations, in order that the quality of past and present records may be determined and proper factors of safety be allowed.

Snow-boards--These stations are maintained mostly in the Rocky Mountain States, the Weather Bureau being the principal agency, although many observations are taken by the Forest Service and reported to the Weather Bureau. The purpose of these stations is to measure the depth of snowfall at the time of its occurrence, and also the water-content thereof before drifting or packing has occurred. Due to the interest shown in recent years in snow-surveys, it is believed that the use of the snow-board is becoming largely a means of measuring precipitation in the form of snow at a given point, and no great interest appears for an extension of these activities.

Snow-courses--Considerable activity has been displayed in snow-surveys during the last decade, as it has been found that measurement of water-content of snow at given places on the watersheds at the end of the snow-season is a valuable means of estimating the runoff in spring. The Bureau of Agricultural Engineering has been especially active in this work, and in making forecasts from its surveys. Since the method used is as yet largely empirical and since several years of observations on snow-courses and of records of stream-flow are required, the work may yet be more or less in its infancy. Arrangements between the Bureau of Agricultural Engineering and the Weather Bureau for collection, forecasting, and publication of the data have been consummated. Much of this work is supported by local agencies, such as States, irrigation-districts, power-companies, etc. Already the work has proved of great value and a considerable extension in the number of stations should be made.

Evaporation-stations--Present observations include 87 first-order stations and 49 second-class or simpler stations. The first-order stations include a complete equipment of meteorological instruments, whereas second-order stations usually include only an evaporation-pan, rain-gage, and maximum and minimum thermometers. The Weather Bureau is the principal agency at present engaged in making these observations. Various types of pans have been used and considerable work has been done in correlating the results of different types of pans with evaporation from a large open water-surface, especially by the Bureau of Agricultural Engineering. Since evaporation does not fluctuate from year to year in the same manner as do some of the other hydrological phenomena, great length of record is not so essential.

Further research is needed, however, in establishing the relationship between evaporation from various types of pans and that from large open water-surfaces. A considerable number of additional stations under various climatic conditions are needed, as is research in the relationship between evaporation from large open water-surfaces and other climatic phenomena which are commonly available from cooperative Weather Bureau stations, particularly that of temperature, in order that evaporation may be more closely estimated at places where limited climatological data exists. Research is also necessary in the field of evaporation from ice and snow.

Stream-gaging--The United States Geological Survey is the principal agency engaged in this work, having 2970 stations operating in the United States, most of these stations being equipped with water-stage recorders from which it is possible to obtain daily records of instantaneous rates of discharge. The Weather Bureau and the Corps of Engineers of the United States Army also maintain a considerable number of stations on navigable streams and streams subject to flood-flows, where in most cases the elevation of the water-surface only is recorded. These stations are maintained primarily in the interest of flood-forecasting and of navigation.

Most of the major streams in the country, the waters of which are utilized to any degree, are fairly well equipped with at least one gaging-station, but more stations are needed on tributaries, particularly in mountainous regions and on watersheds where runoff-conditions are not uniform throughout the watershed. A great deal of the stream-gaging work is on a cooperative basis, financial support being supplied by States and local agencies. Since their financial support fluctuates from time to time, it is essential that a definite network of Federal stations, well distributed in extent, be maintained and supported by the Federal Government, with the cooperative stations continued to supplement these where local interests primarily are served.

Ground-water observation-wells--The recent drought in the Middle West and East has caused nation-wide attention to be focused upon ground-water problems. Prior to that time little attention was paid to ground-water except in those sections of the West where its extent was limited and it was largely used as a source of water-supply. At the present time 6659 observation-wells are maintained by the Federal agencies, 5214 of these by the Geological Survey. Much of this work is on a cooperative basis. A large number of additional observation-wells are needed, distributed throughout the country, particularly in that portion of the United States east of the 100th meridian.

Water-quality; Silt-observations--The occurrence of silt in streams, particularly in the western part of the country, has had the attention of those interested in water-development for many years, since storage-capacity of reservoirs may ofttimes be greatly reduced by deposits of silt, and it then becomes necessary to provide for considerable additional storage-space in order to preserve the needed capacity. Many reservoirs in the West have had their original capacity reduced in a large degree.

The problem of soil-erosion has recently attracted national attention as a result of the recent drought and dust-storms in the Middle West and Southwest, and has given impetus to the collection of data regarding silt. There are now 154 stations being maintained under Federal auspices throughout the country, and this number should be more than doubled.

Silt-observations require daily sampling and should continue over several years in order that a relationship between state of flow and silt-content may be established with a reasonable degree of accuracy. Key-stations should be maintained continuously and at other stations sampling should take place for yearly periods in rotation, separated by several years in between, in order that a check may be had upon watershed-conditions and the trend of silt-content.

Water-quality; Chemical analyses--Sporadic work has been carried on in the past as to the determination of chemical content of both surface- and ground-water, but few continuous series of measurements have been made until recent years. At present, observations by Federal agencies are being carried on at 72 stations in the country. Here, as in silt-observations, it is necessary to make observations continuing over a considerable period of time, at least a year, in order to ascertain the relationship between chemical content and stage of flow. These analyses should include not alone dissolved inorganic matter, but also organic matter and items which affect quality of water for domestic and industrial use and irrigation-purposes. With the growing intensity of development upon watersheds and the increasing use of streams and other water-bodies for disposal of sanitary and industrial wastes, it becomes more and more necessary to maintain a constant check upon the chemical quality of the water in order to determine the increasing effect of upstream pollution.

It is believed that several hundred permanent stations should be established at stream gaging-stations maintained continuously by the Geological Survey, and that in addition several hundred other stations should be maintained for a year's time in rotation so that checks could be made at least five years apart to determine change in conditions. In addition, further work should be carried on in regard to ground-water.

Publication of data--To the person engaged in planning water-enterprises it is not sufficient that observations and measurements of hydrologic phenomena have been in the past or are now being carried on. This material must be readily available in convenient and summarized form if it is to be of value, and information as to the quality and reliability of records must exist.

Excellent work has been done by the various Federal agencies in collecting and publishing these data, but there still remains a large amount of them either published in scattered places far beyond the reach of the average person using the data, or in possession of local or private agencies all engaged in the collection of these data and with the large number of local and private agencies which are now or have in the past been engaged in the collection of same, it is practically impossible for any single agency using the data to have in their library or files all of the material which exists, and the expense of collecting and of assembling such data is usually beyond the scope of any individual agency.

The Federal Government is the logical party to collect and publish such data and while, as stated above, an excellent job has been made of it so far, it is believed that the work could be greatly improved through further centralizing the publication of one type of data in one Federal Department and by the collection, compilation, and publication of all data by whomever collected them in the past, with a careful review of same and comments upon its quality.

Value of basic data--At the present time the Geological Survey and Weather Bureau are spending in the neighborhood of two and one-half million dollars from Federal sources and an additional million and one-quarter from cooperative funds per year in the collection and publication of basic hydrologic data. No information is available as to expenditures by other Federal agencies. The extension of this program in a manner which would meet the needs of present users thereof might call for an initial capital investment of slightly over three and a quarter millions, plus an additional annual expenditure of around one and one-half millions. Annual losses due to lack of adequate data probably amount to 50 or 100 times the latter figure.

In times when everyone is demanding reduction of governmental expenditures it may appear to be unwise to urge an increase. However, one has only to recall a few of the many lives lost, of millions of dollars damage incurred, or of the hundreds of millions invested in water-development enterprises and lost because of insufficiency of basic hydrologic data to realize that the return upon the investment would be tenfold or hundredfold.

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PROBLEMS OF LONG-RANGE WEATHER-FORECASTING FOR THE PACIFIC COA

Geo. F. McEwen

Introduction

Many urgent requests for some advance information regarding the weather along our Pacific Coast indicate both a great economic need of long-range forecasting and a general belief in the possibility of meeting that need. In long-range forecasting the interval may be one or several months or even years, and the procedure is essentially different from that used in making daily forecasts. We are unable to meet the exacting conditions, both as regards observations and our understanding of the physical processes taking place in the atmosphere and ocean, that would be required to make such forecasts in the satisfactory manner typical of the solution of problems in physics or astronomy. Nevertheless, there is convincing evidence that all phenomena, in both the sea and atmosphere, do proceed according to fundamental physical principles. Accurate and reliable forecasting is in general the final achievement in scientific investigations, and the agreement between predictions and observations is the crucial test of theory, but economic needs cannot usually wait until such a stage of completeness has been attained. This is especially true of weather-forecasting for short intervals as well as for longer periods, that is, months or years. Accordingly, in order to do something toward meeting present demands for such long-range forecasts, we are compelled to proceed without a thorough knowledge of all of the details involved. Consequently, present forecasts must be of a general empirical character corresponding to a region rather than to a specified point. However unsatisfactory this situation may be, attention is called to the important fact that all attempts at forecasting are of practical importance if the men directly interested, for example, engineers or those engaged in agriculture, can carry on their work so as to yield better results by considering the forecasts rather than merely preparing for the same average values.

General principles and conditions relative to Pacific Coastal precipitation

Consider now a general picture of some of the major processes going on in the ocean and atmosphere in relation to precipitation and temperature along the west coastal region of North America. Observations of wind and barometric pressure indicate a high-pressure area about a thousand miles west of San Francisco and a low-pressure area over the Aleutian Region. Winds blow out spirally from this "high" in a clockwise-direction and blow in spirally towards the "low" in a counter-clockwise direction. The "high" moves to the northwest in summer, increases in intensity and area, and at the same time the prevailing winds become steadier and stronger. The "low" is especially well developed in winter and disappears in summer. South of the equator the winds are clockwise about a "low" and counter-clockwise about a "high". There is a line of "convergence" (a line toward which air flows from both sides) between the "high" and "low", and directed toward Vancouver Island in winter and Central Alaska in summer. Likewise, an equatorial line of convergence lies between the two oppositely circulating whirls about the "highs" of the North and South Pacific. The whole system shifts several hundred miles to the north in our summer, and to the south in winter. Along the Pacific Coast of both North and South America is a large cold-water belt between the high-pressure areas and the coast, expanding toward the equator. These belts are especially cold and extensive when the "highs" and their accompanying winds reach their greatest development. Consider certain characteristics of rainfall in relation to these conditions and to the following three general principles: (1) Onshore winds are generally accompanied by rain, while offshore winds are dry; (2) polar winds are dry, and winds blowing from lower altitudes into higher are wet; (3) lines of convergence are attended by abundant rainfall.

The Pacific Coast State of Columbia, South America, has rain at all seasons, and is near the equatorial line of convergence. Farther northwards, along the coast from Panama to Guatemala, about 90 per cent of the rain falls during the 6-month period from May to October. The northern Mexican frontier, located in the offshore trade-wind region, is practically dry throughout the year, and north of this region extending as far as Vancouver Island, winter is the rainy season, corresponding to changes in the "high" and "low".

Since the polar line of convergence or line separating cold polar air from the warm equatorial air flowing northward meets the land in the region of southern Alaska and British Columbia, that region has considerable precipitation throughout the year, although it is relatively greater in winter, the season of the greatest frequency of cyclonic storms.

In addition to these regular seasonal variations there are differences from year to year. Occasionally very great departures occur and can be explained by corresponding changes in the ocean. A striking example of direct ocean-influence upon coastal weather is afforded by the westward deflection of the Humboldt Current in 1925, which permitted the warm equatorial waters to penetrate southwards along the coast of South America. This unusual development of the warm counter-current, El Nino, resulted in abnormally heavy rains along the arid coasts of Ecuador, Peru, and Chile. There is some evidence of a recurrence of such a situation about every 35 years.

On the average, the atmosphere contains about five parts of water-vapor per thousand parts of air by weight, and the higher the temperature the greater is the possible amount of atmospheric water-vapor. This invisible vapor when cooled sufficiently condenses, forming fogs or clouds. Minute electrified particles, or ions, widely distributed throughout the atmosphere, act as nuclei which facilitate this condensation. Even the densest clouds contain only about five parts of water in a thousand parts of air by weight and further cooling, necessary to produce precipitation, forms drops of water about one-eighth inch in diameter, which may fall as rain. Sufficiently strong upward air-currents may raise drops of water thus condensed, and such low temperatures may prevail as to freeze small drops and successive layers of water condensed on them thus forming hail. The cooling required for precipitation may be brought about by mixture with relatively cold air, by a flow towards regions of higher latitude where a relatively lower temperature prevails, or, most important of all, by expansion due to rising into layers of lower pressure.

A good example of conditions favoring the production of rain is afforded by the warm moist ocean-winds blowing to the northwest from the Indian Ocean and turning to the northeast across the Arabian Sea and the Bay of Bengal during the northern summer. These monsoon winds, after passing over a warm ocean-path some 4000 miles in length, become saturated with moisture at a relatively high temperature. Wherever these winds are directed against steep slopes of coastal mountain-chains, the air may be deflected upward with sufficient velocity to produce such a rapid fall in temperature as to cause heavy precipitation called orographic because of the influence of topography. Where the winds descend over the warm land-surface, the air takes up any available moisture, and precipitation is impossible.

Air warmed from below, as often happens in winter when the air is colder than the sea, is unstable, and orographic rainfall is thereby aided. On the other hand, when air is cooled from below, as is often the case in summer over the cold inshore water-belt of our California Coast, there may be low fogs or mist. But these conditions cannot cause orographic rains.

A different but very important condition producing a rapid updraft of air independently of local topography often develops at a surface of discontinuity or a "front", separating warm and cold air at the same level. Warm winds converging toward colder winds rise above the colder air, and their moisture is thus condensed in the same way as it is in air rising up mountain-slopes. Thus our cyclonic storms develop. In fact, the weather of the whole Northern Hemisphere is controlled by advances and retreats of the polar front at which polar and equatorial air meet. Warm air flows along the surface of the earth and sea from the subtropic "highs" toward the polar regions, concentrating in warm tongues and continuing into the polar regions at the upper levels where it cools, and later reaches the lower levels. Thus, masses of cooled air accumulate behind the polar front and cause it to advance southward. At places of least resistance, great masses of cold air break through and are expelled in the direction of the tropics. This results in a northward retreat of the polar front, after which the process is repeated. Moreover, this intermittent quality of the general atmospheric circulation is especially characteristic of the winter, when marked discontinuities of sea surface-temperatures prevail. Then a succession of cyclonic storms, traveling eastward, develops. Both the irregular and seasonal displacements north and south of the polar front result in a corresponding migration of the tracks of these storms, and the position and intensity of the North Pacific "high" determines how far south they reach the North American Coast. Finally, the sea surface-temperatures determined by solar radiation, evaporation, and the varying ocean-currents, are a fundamental control of the "high". Thus we are led to regard the ocean and overlying atmosphere as parts of a great and complex mechanism driven by energy derived from solar radiation. Among the processes going on in this mechanism are currents of air and water, both horizontal and vertical, mixing within each fluid, evaporation, precipitation, and radiation. These processes are all interrelated and involve changes in the distribution of matter and transformation of energy. In this connection it is helpful to recognize that atmospheric moisture is carried from the ocean over the land, precipitates as rain or snow, returned as runoff to the ocean, and evaporated into the atmosphere, thus completing a cycle of change.

How can we use our knowledge of these general conditions and physical principles for the purpose of obtaining some indication of weather to be expected? All investigators in dynamical meteorology and oceanography are contributing to the ideal of explaining quantitatively the observed atmospheric and oceanic phenomena. For example, valuable information as to the physical mechanism of the weather will no doubt result from special investigations made from the dynamical standpoint such as the one carried out at the Scripps Institution by Horace Byers in which the "air-mass" concept is the basis. Such information is probably essential to progress from empirical methods of making quarterly forecasts. No doubt, all will agree that the most satisfactory method of forecasting is a deductive one founded on established cause and effect relations to which rigorous quantitative studies lead. However, while such investigations are in progress, and long before an approximate realization of this ideal, valuable suggestions regarding possible indices of forecast-value may be found.

Forecasting by correlation-methods

In this complex world-mechanism there may be a considerable time-lag between certain causes and their effects. Accordingly, investigations of indices of such causes should give advance information regarding the accompanying effect. Moreover, any effect, that is, seasonal precipitation over a region, must in general be regarded as resulting from a series of causes of varying importance and involving various time-lags. Accordingly, as is usual in such complex phenomena, the natural procedure is, especially in the early stages of the investigation, to search for all possible indices and, by appropriate statistical methods, to work out empirical relations between these indices and weather-conditions. In this way indices of primary significance can be discovered by trial and error and evaluated in accordance with principles of probability. The English meteorologists, Blanford, Eliot, and Sir Gilbert Walker are recognized as pioneers in applying this general method, in predicting the monsoon rains in India. It is the method by which our trial-forecasts were begun and continues to receive our main attention.

Evidence is accumulating in support of a correlation between the general trend of sea-temperatures and atmospheric temperatures and between each of these and the general trend of precipitation, and in our latest studies we have used sea-temperatures throughout the calendar year for forecasting seasonal precipitation. This required a forecast of winter-temperatures which has been accomplished by means of an extrapolation-method applied to smoothed temperature-observations. The gradient between winter and late fall sea-surface temperatures also appears to be an important advance index of precipitation. Another suggestion is the possibility of a cyclical change in the sign of the coefficient of correlation between an index, such as summer inshore surface-temperatures, and the following seasonal rainfall. A classification of weather-elements with reference to geographical regions is being used, and an analysis of storm types in accordance with sources--that is, storms entering from the north or the south--are regarded as important and should result in better correlations with advance indices.

While conducting a continuous investigation of certain oceanic phenomena at the Scripps Institution Pier near La Jolla, in southern California, an inverse relation was indicated between sea-temperatures observed during the summer months and the amount of rain falling during the following winter months. This continuous series of observations began in 1916 and up to the present time indicates that the lower the summer temperature, the higher will be the rainfall in southern California during the following winter or rainy season. During the 10-year period 1916-26, this simple empirical relation continued to hold with remarkable accuracy. However, as stated earlier, it would be surprising if such a simple empirical relation as has been found for a short time-interval should continue to hold thus accurately in the case of as complex a system as the ocean and the atmosphere. Yet the close relation already established between oceanic and atmospheric phenomena generally, tends to give weight to such a result.

Forecasting by means of cycles

Investigations over the longer period 1916-35 indicated relatively more departures from the simple relation of precipitation to temperatures. A better result, considering this interval as a whole, was obtained by regarding the seasonal rainfall as having natural cyclical variations subject to disturbances whose relative magnitudes were indicated by the summer minus the preceding winter ocean-temperature. Values of the 5-year cycle-factor, Y, found to be especially prominent, are given in Table 1, where negative values correspond to a deficiency.

Table 1--Values of 5-year cycle-factor Y

Year	Station		
	San Diego	Crescent City	Portland
1930-31	-0.4	1.6	1.0
1931-32	0.6	7.2	0.3
1932-33	0.3	-0.5	3.5
1933-34	-1.3	-9.2	-2.3
1935-36	-1.5	-1.7	-3.0

Investigation of precipitation-cycles in the Southern California Region shows an approximate symmetry centered at the season of 1910-11 and indicates five low values at intervals of about 15 years during the period since 1865, the last being in 1933. During the same period six high values are shown at intervals of about 15 years, of which the last may be expected between 1940 and 1945, thus corresponding to a general upward trend for the next five or ten years.

We are carrying on investigations of possible "natural cycles" in weather-phenomena with the aid of special methods of analysis. The method of strato-analysis developed by the engineer, A. Streiff, appears to be well adapted to such studies, and has revealed cycles of about the same period in several different groups of data on rainfall, runoff, and lake-levels. In this connection we believe tree-ring and clay-varve data may be used as indicators of rainfall-cycles. Such records are especially valuable because of their great length, but the processes result from a complex of causes, difficult to analyze. Therefore, special care and attention to the details of these processes are needed to avoid serious errors of interpretation. We use the cycle-method as a supplement to the correlation-method in forecasting, and, except for short cycles, a few years in length, regard this method as better adapted to indicate what may be expected over a period of years rather than for a specific season.

Forecasting based upon cosmical influences

We have proceeded on the idea that, in the present state of knowledge, attention directed primarily to the various measurable phenomena taking place in the atmosphere and ocean is essential to a solution of forecast-problems. A thorough study of the mechanism of precipitation might in time reveal the main factors controlling it and thus yield a trustworthy method of forecasting the amount, months in advance. Evidently oceanic phenomena would play an important part in such a procedure. Also, a valuable forecasting index that may materially improve present results may be derived from the extensive air-mass analyses that will be carried on to an increasing extent.

However, we are ready to make such use of the extensive work on solar radiation and sunspots that we find to be of help. The cyclical nature of the action of the planets on the Sun in producing sunspots and the possible direct electrical action of the Sun in producing vortices in the Earth's atmosphere afford a field that should be investigated. Again, the long-period ocean-tides depending upon changes in planetary configurations may have some forecast-value and are being investigated by others.

Temperature-forecasts

Reliable forecasts of monthly air- and sea-temperatures one or several months in advance, are in great demand. In fact, attempts to provide such information for commercial purposes are made by various individual organizations: Utilities, department stores, sea-products companies, etc. May we expect to be able to work out such forecasts with sufficient reliability to be of commercial value?

While no adequate physical theory for guidance in such problems has been developed, it seems reasonable to assume the existence of factors influencing the temperature-trend a few months in advance. While searching for the proper factors, it is assumed that a composite index of them having forecasting value is furnished by past temperatures. Proceeding empirically on this basis, the monthly temperatures are smoothed or adjusted in order to eliminate irregularities which at first are regarded as accidental. Projecting these smoothed values a few months in advance in accordance with past variations, and correcting the seasonal changes for systematic errors introduced by the smoothing process, provides an empirical forecast. Such a procedure has been applied to observations over a period of about 20 years in order to compare the computed and observed temperatures. A very definite correlation was found, indicating that a temperature-forecast three months in advance by this method departed from the actual by more than a degree in only 10 per cent of the cases for sea-temperatures at La Jolla. Air-temperatures at Riverside were thus forecast to within two degrees of the actual in about 90 per cent of the cases. The success of such an empirical procedure depends upon the stability of the general temperature-trends. The limited experience with this method in southern California indicates that it is of sufficient reliability to be commercially useful.

There is evidence of a four-year temperature-cycle, the last minimum being in 1933. As a result of this study the following statement was issued in the spring of 1934: "The general upward trend thus indicated from 1933 to 1935 is in accord with the three months' forecast of higher than average temperatures for the summer of 1934." There was a general agreement of observations with this forecast of summer temperatures.

Tentative explanation of sea-temperatures as indices of seasonal rainfall

The observed relation of seasonal precipitation to inshore sea-surface temperatures accords with the following hypothesis. Because the rainfall in California depends mainly upon the flow to the east of a mixture of air and its accompanying moisture evaporated from the Pacific Ocean, the greater the amount of air thus transferred, the greater will be the amount of water-vapor available for precipitation. Moreover, the mass of air that is thus transferred to the land during winter should be proportional to the initial mass over the ocean. Therefore the greater the intensity of the barometric pressure in the high-pressure area over the ocean during the summer, the greater should be the rainfall during the following winter or rainy season. This periodical or seasonal interchange of vast masses of air between the ocean and continent varies in average amount from year to year. Moreover, it is not a uniform or regular process; there is a continual disturbance of equilibrium tending to restore a balance, thus resulting in a succession of atmospheric disturbances which we call storms. Although detailed barometric observations may not be available for any one year over the Pacific, the inferred correlation between the intensity of this high pressure and the decrease of surface ocean-temperatures below the normal enables us to use the ocean-temperatures as an index of the pressure-distribution, and accordingly of the expected rainfall.

Actually, the sea-temperature is an index of a complex of conditions related to our weather. Accordingly, it was expected that additional factors of forecast-value in the complex and interrelated atmospheric and oceanic masses would be discovered as the investigation progressed.

This tentative explanation is based upon fundamental researches in physical oceanography carried on at the Scripps Institution, where particular attention has been given to problems of oceanic circulation, evaporation, turbulence or eddy-motion, and radiation. This work has involved the applications of principles developed by other investigators in these fields, the formulation of additional methods, and their application, and the making and collection of appropriate observations.

From what has been presented already regarding the problem of long-range forecasting on this Coast it should be evident that investigations of the direct problems suggested by forecasting are difficult and expensive. While a few individuals devoting their whole time to this type of research might produce quite valuable results, the task is obviously so great that only relatively slow progress can be made by the part-time attention of any one whose main work is physical oceanography. Specific questions requiring special attention such as horizontal and vertical circulation in the sea, evaporation, and solar radiation arising as parts of the large problem, each should have the undivided attention of especially qualified investigators. While these, and other, researches being carried on at oceanographic institutions may contribute to the forecasting-problem, a selected group of meteorologists or a special governmental agency should be concentrating attention on the larger forecasting-problem.

Conclusion

In dealing with so complex a problem as long-range weather-forecasting, the writer has proceeded along lines shown to be most promising by past experience, at the same time keeping an open mind for all possible methods of attack. It appears desirable to hold a forecasting-system in a "fluid" state rather than in a rigid unchangeable one. Here on the Pacific Coast, where every clue as to the probable nature of the weather to be expected is so eagerly sought, it is imperative that careful unbiased consideration be given to the important question of evaluating the methods used. All interested hope that the combined efforts of those meteorologists who enter the field of long-range forecasting will meet with success commensurate with the increasing demands for such service. Finally, attempts to make long-range forecasts for one region continue to indicate that weather is not simply a local phenomenon having purely local causes. The value of indices relating to conditions far from the region for which forecasts are made, is being demonstrated; thus long-range weather-forecasting is necessarily a large-scale cooperative undertaking. Results commensurate with the increasing demand for such forecasts can evidently not come from only a few individuals giving part-time to the problem.

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THE RELATIONSHIP BETWEEN TREE-GROWTHS AND STREAM-RUNOFF IN THE TRUCKEE RIVER BASIN, CALIFORNIA-NEVADA

George Hardman

During the past 20 years a decline in the precipitation on the headwaters of the streams has occurred. Because the drought-years in this interval have been accompanied and intermixed with so many good seasons, the change was not, until recently, recognized as a definite trend.

The possibility that the present drought might be due to a definite downward trend in precipitation has stimulated interest in the subject of the weather, and especially in the possible presence of cycles in precipitation. This interest is particularly keen in the areas dependent upon the annual flow of streams for irrigation-water.

In general, the weather-records cover too short a period to reveal long-time trends or cycles; hence other records are desirable. For this reason a study of the relationship between tree-growths and the runoff of the Truckee River was undertaken. If any correspondence between these two phenomena could be established, it should then be possible to extend the history of the runoff of the River to correspond to the period covered by trees living in the river-basin. Since many 400-year-old pines can be found, a record of this length should be possible.

The possibilities in the study of tree-rings were first recognized by Dr. A. E. Douglass of Arizona about 1901. The technique developed by Douglass for measuring, standardizing, and comparing tree-specimens has become the standard for this work. In the present work his methods have been followed rather closely.

The studies on the Truckee River Area, which were started in August 1934, have been confined to the western yellow-pine, which grows abundantly on the hills in this river-basin. The samples for this study were all collected by the author from carefully selected trees, the samples being taken with a Swedish increment-borer and an extension which permitted the taking of bores to a depth of three feet.

All of the trees were chosen from well-drained sites on the lower margins of the forests where it seems that the moisture received from the annual rainfall should have greatest influence on the growth of the trees. Most of the samples were taken from trees growing in the altitude-zone between the 5500- and 7500-foot contours. Since the work was started, over 200 trees have been sampled and more than 50,000 individual rings have been measured. From this group, 46 trees with good records for 200 years and 15 trees with good records for 400 years have been selected for comparison with precipitation and runoff.

To compensate, to some extent at least, for the effect of lag due to conservation of moisture by the soil, all the data have been smoothed by taking running averages of five and three. This treatment also takes off the peaks of the highs and lows, and brings out trend-effects more clearly.

For comparison and correlation with the data from the tree-growths, the runoff of the Truckee River, exclusive of Lake Tahoe, at State-Line, and the average precipitation of the six high-altitude stations of Auburn, Colfax, Grass Valley, Nevada City, Placerville, and Summit were used. The charted data show a fair parallelism between the tree-growth and (stream-runoff) precipitation-curves, and a rather close agreement between the tree-growth and stream-runoff curves. A mathematical correlation-figure of 0.88 for the tree-growth and stream-runoff data for the Truckee River, and similar figures for other streams draining adjacent areas of the Sierras, support the conclusions reached from the graphs.

The basic assumption that within the area of forest included in this study the moisture available governs the growth of the trees and that the rate of growth gives a measure of the runoff in the streams seems to be well supported. In this connection it might well be pointed out that in this study the objective has been to trace trends in tree-growth and runoff and not to determine annual variations in either of the two factors.

From the history revealed by the tree-growths it seems that this area has experienced a succession of periods of dearth and abundance of moisture for the entire 400 years covered by the record. It would seem that at least one major drought may be expected each century. Also, there is some basis for the belief that during the period from about 1870 to 1915 the moisture-supplies were considerably more abundant than for any similar period during the past 400 years. On this basis such a period cannot be expected to be repeated very soon.

The data have not been subjected to exhaustive analysis for the presence of cycles in precipitation, but they are not apparent on superficial examination.

From an economic standpoint the firm irrigated acreage on a project should be confined to the acreage irrigable during the periods of low annual runoff. This fact takes on added significance from the apparent inevitability of the recurrence of droughts at fairly regular intervals as shown by the tree-growth record.

The results of this study are available in a more complete form in Bulletin 141 of the Nevada Experiment Station.

Comments on differences between the results of the above studies and those of Davis and Sampson in the Lakeview (Oregon) Area (see next paper)--In the studies by Davis and Sampson correlations between tree-growths in the Lakeview Area and the precipitation-records of a number of Weather Bureau stations were attempted. The results not only indicated very little correlation between tree-growths and precipitation but also gave divergent results between groups of trees within the area.

The lack of agreement between the tree-growths and the weather-records is not surprising. The weather-stations are located in the valleys at some distance from the mountains where the trees are growing and it is doubtful that such data can be used in all cases with certainty as an index of the rainfall in the more mountainous areas.

The records from individual weather-stations often show inexplicable variations. This is especially true of the records from valley-stations where the average rainfall is very low. Individual storms often tend to be more or less localized and a single heavy storm concentrated over a single rain-gage may give a record for that gage entirely out of harmony with the average precipitation for the area. For instance, the record for the Reno station shows a very high precipitation when the average for the whole Sierra Region is low. Sometimes the precipitation for a number of years at Reno shows trends in exact opposition to those of the high Sierra stations and to the trends in runoff of the Truckee River.

The divergence in the rates of growth between groups of trees in the same area is more difficult to understand and no explanation could be attempted without an exact and intimate knowledge of the whole forest-area. Perhaps the reasons may lie in the history of the area, which history may be difficult or impossible to trace. Possibly the use of larger groups of trees might obviate this difficulty.

The quantity of water available to the trees may, perhaps, not always be the limiting factor in forest-growth, but it would seem that in the areas of low annual precipitation and in the critical zone along the margins of the forests, moisture is most likely to be the limiting factor. The problem would seem to be that of finding a reliable measure of the amount of moisture available for the use of the trees.

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EXPERIMENT IN CORRELATION OF TREE-GROWTH RINGS AND PRECIPITATION-CYCLES

Wendell E. Davis and Arthur W. Sampson

The problem--In 1931 a group of landowners whose properties bordered Goose Lake, in Modoc County, California, requested their farm advisor, John C. Hays, that a study be undertaken of the cycles of the Lake water-level. It has been reported that the Lake has filled to overflowing and receded to dryness three times since history has been kept for the region. At one time regular steamer-service operated from a point near Alturas on the southern end of the Lake to Lakeview, 30 miles north. The Lake is dry at the present time; incipient drying was evident about 1916, and by about 1923 it was completely dry. Herbaceous vegetation has for some years virtually covered the old lake-floor and ranching improvements, such as fences and wells, are becoming established farther and farther out on the old bottom. The question in the minds of the people in the area is: Will the Lake again refill? If so, how long before this may occur?

The request given the farm advisor was transmitted to Dr. A. W. Sampson, who immediately became interested and enlisted the cooperation of the senior author of this paper, at that time a graduate-student of the Division of Forestry of the University of California. Though the original question remains unanswered, the analysis has led to a thorough appraisal of the behavior of tree-growth to the climatic environment in this region.

The question appeared to resolve itself into one of precipitation-cycles. The present paper deals with the annual ring-widths of ponderosa-pine in this area in relation to the annual precipitation of the region. Should variation in tree-growth and fluctuation in precipitation be found definitely related, then a rainfall-record could be extended back as far as growth-records extend and forecasts made on the basis of the periodic cycles evident from the analysis.

The range of precipitation in this county is from about eight inches to about 27 inches a year with an annual mean of 14 inches. Ponderosa pine (_Pinus ponderosa_) is clearly the dominant tree-species in forest-stands of the region where it is associated with white fir (_Abies concolor_), red cedar (_Thuja plicata_), and western juniper (_Juniperus occidentalis_).

Site and specimen-selection--The growth-specimens for study were collected in 1931. Three locations were selected, each with representative stands of ponderosa pine. They were within about 20 miles of each other and distributed in such a way as to be proximate to the three sources of weather-data in the region, namely, Lakeview, Fort Bidwell, and Cedarville. The record at Lakeview began in 1884, the one at Cedarville in 1894, and that of old Fort Bidwell in 1865. The stations at Lakeview and Cedarville supply temperature-records as well as precipitation-data. The areas were chosen to be uniform in soil and exposure. The slopes are steep; hence the chance of moisture being impounded during dry seasons would be remote. Only those trees were taken which gave no indication, either from examination of the site or from ring-record on top of the stump, of any sharp fluctuation in growth which might be attributed to such disturbances as defoliation by lightning, insect-attack, or soil-slippage. No tree was selected for sampling which was closer than 50 feet to a neighbor; thus selection of areas and manner of sampling, together with the fact that soil, slope, and aspect remain virtually constant through the lifetime

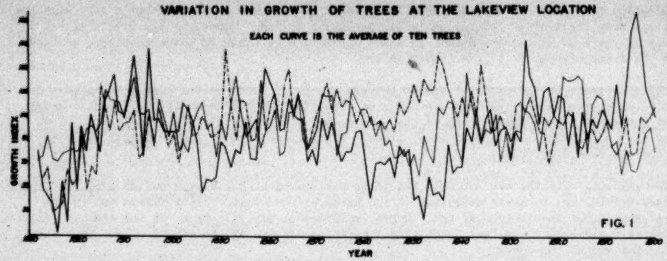

FIG. 1

of a tree, should leave fluctuations in the growth-record to correspond to the result of fluctuations in local climate. Radial sections of stumps of 90 recently logged trees were taken, the growth-record of which averaged around 400 years. Several of the trees date back before the year 1400. The degree of fluctuation in the growth-records, as well as the extent of individual variation among trees in a group, is shown in Figure 1. The material from the Lakeview location has been broken into three divisions of trees and averages for each plotted separately.

Measuring and dating of material--The ring-record was collected by sawing a slab from the top of the stump. These slabs were later cut radially so that a piece about two inches square, extending from the bark through the center of the tree, was obtained. From these carefully sanded radial pieces, measurements were made by using a specially constructed machine reading to 0.01 mm.

Because the material was collected from stump tops of timber-sale areas, dates at which trees were cut were not known. In order to date this material, increment-core borings were made from 30 living trees on each area. Cross-dating was accomplished by a graphic process, introduced by Dr. Douglass, and known as a dating-chart. The method is so sensitive that reliable dating may be secured even though growth-trend of an individual may be erratic.

Calculating effect of age-trend, moisture-lag, and tree-dormancy period--Growth-data contain three types of fluctuations, namely, seasonal fluctuation, cyclic fluctuation, and age-trend. Declining growth of the tree due to senility was eliminated from the data by drawing an age-trend curve through the growth-record of each individual tree (before averaging for the group is made) and expressing the growth as departures from it. This leaves all fluctuations in growth-curve to be accounted for by cyclic and seasonal fluctuations. The climatic record, however, must be corrected for the influence of rainfall in the preceding year. The amount of moisture hold-over from year to year is a matter of soil-depth and texture. The selection of the "moisture-lag" correction-curve to be used is hence determined by trial and the one which most strengthens relations between growth and climatic data is used. In addition to determining moisture-lag from year to year, annual totals of precipitation must be corrected to coincide in time with yearly growth-period. This is also a trial procedure. It was found for the region studied that the expression of annual rainfall from September 1 to September 1 gave the strongest relationship. Temperature-data were also used to further determine this arboreal year by identifying the end of the growing season each year and then totalling the rainfall toward the next season from that point.

Statistical analysis--Following collection, measurement, and preparation of data, analysis was taken up. The correlation-coefficient for relationship between the average tree of group A, and corrected precipitation-record at Lakeview, 14 miles distant, was 0.24. This figure is more significant in view of the fact that the relation between growth and precipitation for other tree-groups and adjacent precipitation-records was even less. This correlation explains, on the average, less than six per cent of the variance in annual growth. Upon further investigation it seemed that an inverse relation exists between annual rainfall and temperature in this region. Years of heavy rainfall tended to be accompanied by temperatures below average. Thus to secure a true relationship between precipitation and tree-growth, a joint analysis of growth as a function of the three variables, precipitation, temperature, and length of growing season was made, in which the relationship of each of the factors to growth were determined while other factors were simultaneously held constant. The multiple correlation-coefficient is 0.37, with a standard error of 0.14. This implies that in two samples out of three the maximum explained variance in growth in this region on the basis of precipitation, temperature, and length of growing season is 26 per cent, with a positive explained variance of somewhat over five per cent. The regression-coefficients show that in this region precipitation ceases to be a determining factor of growth where it is above 29 inches per year; that temperature is not a critical factor in growth through any of its range; and that the length of the growing season exerts no influence when it is over 180 days. However, the zone of error of the lines of regression from which this statement is drawn is so wide that little dependence can be placed in the relation of growth to any of the three climatic factors.

Upon studying seasonal distribution of precipitation it is seen that annual trends in rainfall are not reflected by seasonal components. There is a possibility that annual growth may be molded largely by the amount of rainfall received during the growing season and that the relation between growth and precipitation is hidden by the discrepancy of the precipitation during the balance of the year. Correlation-coefficients between annual growth and rainfall for the whole growing season, the fall portion of the growing season, the precipitation in winter, and the water-equivalent of the snow at the end of the winter period, were computed. No significant relationship was found.

Conversely, the possibility exists that variation in growth from year to year may be largely confined to the spring or the summer portion of the annual ring. Those easily identifiable portions of the annual increment were separately measured in all of the growth-material. Spring wood shows a closer relationship to annual precipitation than summer wood. However, for the region studied, this relationship is not strong enough to be significant.

Discussion of results--The foregoing analysis has been made from data secured from thorough and representative sampling of trees on carefully chosen locations. All available measurable factors of the climatic environment have been considered. As already indicated, the material was selected in such a manner as to be as free as possible from all influences on growth other than climate. The results obtained have not indicated any significant association between annual precipitation and annual radial growth. The study supports the much-expressed conclusion that interaction of plants to their environment is so complex that the existence of relationship of any one physical factor to plant-function is obscured. Because of differences in depth and texture the water-retaining capacity of soils varies. In years when precipitation is poorly distributed a great portion is lost on soils having low water-retention power. Consequently as much moisture may be made available to a tree from ten inches of precipitation well distributed through the normal precipitation season as from 20 inches occurring as high-intensity rains.

In observing growth-record itself, it is seen that strong cyclic tendencies exist in the data from the year 1400 to the present. Correlation-coefficients were compiled in which this cyclic trend was removed by computing standard deviation of the series from trend-line rather than from mathematical average. Here no correlation is found, thus showing that the amount of association which does exist between growth and precipitation in this region is due to trend and not to seasonal fluctuation. Failure to find strong correlation between growth and precipitation, however, should not be interpreted to mean that the causes of the fluctuations in growth are not fundamentally climatic. Rather, it should be concluded that physiological activity of the tree cannot be plotted as a function of net annual rainfall deposited on soil-surface. The influences affecting rainfall from the time of precipitation until absorption as nutrient solution are innumerable, and one important one is the intensity of the precipitation itself. The nutritional functions of the precipitation from time of absorption as nutrient solution until it is incorporated in radial growth of the tree is likewise the result of many influences. Thus our study of relationship of growth to precipitation becomes three-dimensional with the functions of precipitation, time, and growth all keeping pace. To express precipitation-totals such that their nutritional function in the tree would be rigidly evaluated might conceivably explain why one fails, in some regions where precipitation would clearly appear to be a dominant factor in the limitation of growth, to find annual growth-rings of trees to be dependable indicators of precipitation-cycles.

Conclusions

(1) The annual precipitation, although limited locally, and the growth of trees as measured by their annual rings, are not related to each other in the region studied.

(2) The yearly trend of precipitation explains on the average 14 per cent of the trend of growth of ponderosa pine in this area. The variance in growth is largely unexplained by the precipitation-factor; consequently the development of a precipitation-curve based on the tree-growth records would not be dependable.

(3) The causes of tree-growth fluctuations are indicated to be fundamentally climatic. The complexity of the interaction of trees to their environment obscures this relationship when the moisture-values are expressed as net annual precipitation.

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THE DIURNAL FLUCTUATION IN THE GROUND-WATER AND FLOW OF THE SANTA ANA RIVER AND ITS MEANING

Harold C. Troxell

(Published with the approval of the Director, U. S. Geological Survey)

In the time alloted for this subject it will be impossible to discuss, in its entirety, all phases of the methods used in computing the loss of water by transpiration from native plant-life along the Santa Ana River. The results of this work are published in Bulletin 44 of the Division of Water Resources, State of California. The present paper is confined to a discussion of the diurnal fluctuations that occur in the flow of the Santa Ana River and the adjacent ground-water.

On Figure 1 have been plotted the gage-height records for a short period (July 5-8, 1935) for eight southern California streams. These records have been selected at random from the large number of records filed in the local office of the United States Geological Survey. Some of these streams have a large drainage-area, others are small; some are short and steep, others flat and long. The points of measurement range from 15 to 2950 feet above sea-level. One of the streams (Mojave River) is in the desert-region; the others drain into the Pacific Ocean. The object of Figure 1 is to demonstrate that the diurnal fluctuation exists and is, to a large degree, similar at most points of measurement. As a rule, the maximum discharge occurs about 10 o'clock in the morning, and the minimum late in the afternoon. It is readily recognized that these fluctuations are in the main caused by the evaporation and transpiration-loss in or adjacent to the stream-channel.

It has been the practice of many engineers to assume that the record during the period of greatest discharge, usually about 10 o'clock in the morning, represents the period of minimum transpiration-losses, and the period of least discharge, in the afternoon, represents the maximum transpiration-losses. Others have connected the points of maximum discharge during the diurnal fluctuation and assumed that the curve thus obtained would represent the probable flow of the stream if there were no losses, also that the difference between this quantity and the actual discharge represents the transpiration-loss. I shall attempt to demonstrate that, as a general rule, these assumptions are entirely in error, with the tendency to give results considerably less than the actual transpiration-loss.

On Figure 2 is plotted a copy of the record of water-stage recorder for four of our regular stations on the Santa Ana River for the period July 15-24, 1932. The station at Riverside Narrows is at the Union Pacific Railroad Bridge near Riverside (Arlington). The Hamner Avenue station is 8.2 miles downstream. The Auburndale Bridge station is 11.8 miles below Riverside Narrows, and the Atchison, Topeka, and Santa Fe Railway Bridge station is 16.6 miles below Riverside Narrows. Well E-3 is 13.8 miles below Riverside Narrows, almost half way between the Auburndale Bridge and Santa Fe Railway Bridge stations. The average velocity of the stream-flow in this section of 16.6 miles of channel during the non-flood period is about 1.5 feet per second, or 1.0 mile per hour. Well E-3 was especially dug for this study, on the river-bank about 30 feet from the River.

The large amount of fluctuation noted in these river-records is due to the scouring and filling of the stream-channel and the passage of sand-waves. Notwithstanding this tremendous amount of minor fluctuation, there is a well-defined daily cycle. These records show considerable similarity. They all approach the maximum flow, as well as the minimum, at approximately the same hour.

The record obtained on the ground-water table at Well E-3 is not unlike the river-records, especially that at the Santa Fe Railway Bridge.

In addition to Well E-3, two other wells were dug on the banks of the Santa Ana River in the same vicinity. Well E-1 was 970 feet north of E-3 and 1000 feet from the River. Well E-2 was on

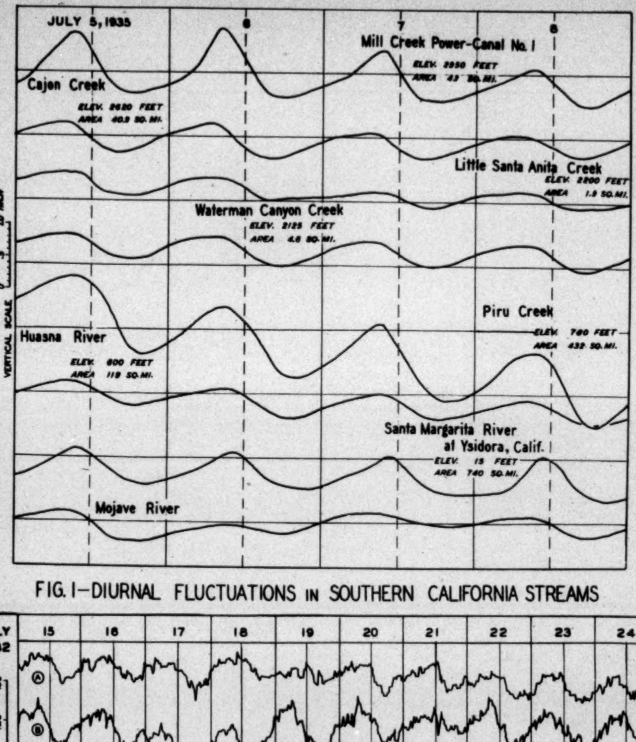


FIG. I—DIURNAL FLUCTUATIONS IN SOUTHERN CALIFORNIA STREAMS

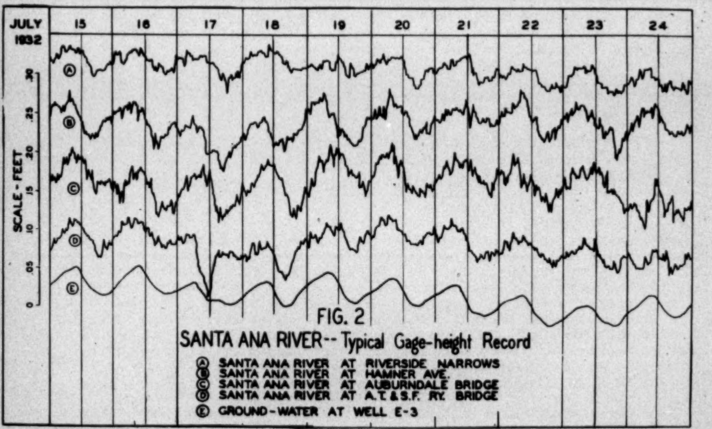


FIG. 2

SANTA ANA RIVER--Typical Gage-height Record

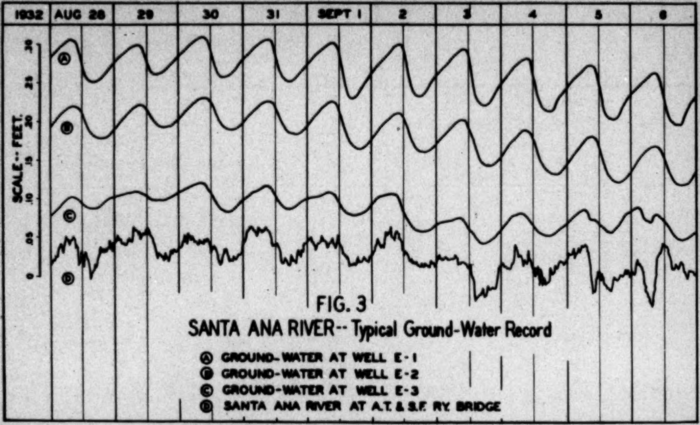


FIG. 3

SANTA ANA RIVER -- Typical Ground-Water Record

a line between E-1 and E-3, about 430 feet from the River. The record from these wells for the period August 28 to September 6, 1932, is given on Figure 3.

The diurnal fluctuations at this group of wells are all to a certain degree similar to the river-records. The water-table is highest around 10 a.m. and lowest about 6 p.m. At the bottom of Figure 3 is given the record obtained at the Santa Fe Railway Bridge. The records obtained at wells E-2 and E-3 show how the amplitude of this diurnal fluctuation is modified as it approaches the River from Well E-1.

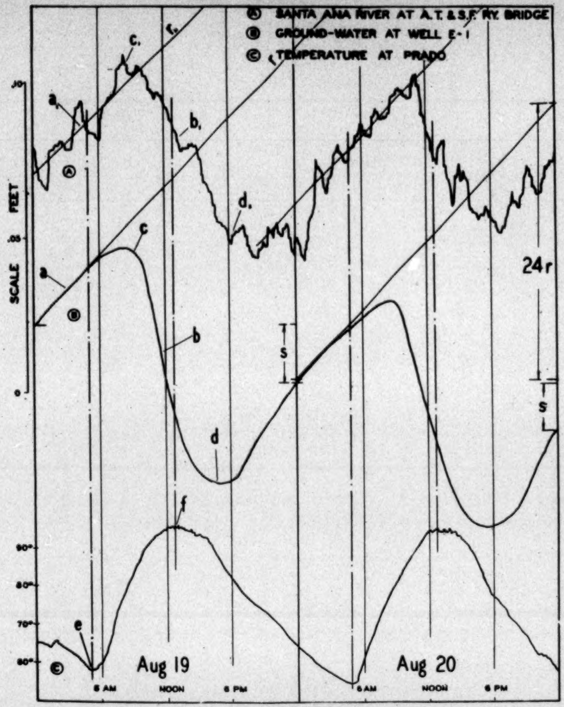
In passing, it should be stated that there is a moderate amount of regulation in the River directly above wells E-1 to E-3. For example, on July 17 the discharge in the River was reduced between 6 a.m. till the afternoon. The record at Well E-3 was modified on that day, notwithstanding the fact that the water-table is usually about 0.2 foot higher than that in the River. Similar effects of regulation are shown on September 5 and 6.

The object of Figures 2 and 3 is merely to show that a diurnal fluctuation occurs both in the River and in the ground-water table adjacent to the River, and that these fluctuations are to a degree similar.

On Figure 4 have been plotted the records of ground-water fluctuation at Well E-1, the gage-height record of the Santa Ana River at the Santa Fe Railway Bridge, and the temperature-records for the 2-day period August 19 and 20, 1932.

It can readily be established that the diurnal fluctuation shown by the record of ground-water at Well E-1 is due, in the main, to transpiration-needs of the plant-life. The water to supply these needs can be drawn from the inflow to the area or from ground-water storage, or from both. Thus, for example, at point c the ground-water table remains at a constant altitude for a short period. This means that during this period the inflow to the ground-water table is sufficient to supply all the transpiration-demands. At point b the transpiration-demands are not only using all the inflow but are also making a heavy drain on the ground-water supply. At point d the transpiration-losses have decreased to such a point that the inflow is again sufficient to supply these needs. At point a the transpiration-needs are much less than the inflow, and as a result the surplus water is placed in storage, causing a rise in the ground-water table. It is thus apparent that the ground-water record is merely an accumulative curve of the rates of ground-water inflow (plus) and the transpiration-use (minus).

The maximum transpiration will occur at the point showing the maximum rate of drop in the ground-water table. This point is indicated by b on the Figure. This point of maximum use oc-



1932
FIG. 4—SANTA ANA RIVER
Effect of Evaporation and Transpiration on River and Ground-water Elevations

curs at or near the time of maximum temperature. Likewise the point of minimum transpiration will occur at the point showing the maximum rate of rise in the ground-water table, such as is indicated by a. This point agrees fairly well with the time of the minimum temperature.

This is in entire agreement with the work of C. A. Taylor (Rainfall-penetration and consumptive use of water, Calif. Div. Water Resources Bull. 33, 1930) at Ontario, California, who demonstrated that transpiration from native water-loving vegetation agreed closely with temperature. Figure 5 gives a section of his record, which shows a fine correlation between the diurnal temperature- and transpiration-cycles.

Walter N. White, in the United States Geological Survey Water-Resources Bulletin of March 10, 1927, suggested that it was possible, by means of records similar to that shown on Figure 4, to determine the daily transpiration. (See also W. N. White, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: Results of investigations in Escalante Valley, Utah, U. S. Geol. Surv. Water-Supply Paper 659, pp. 1-105, 1932.) If the

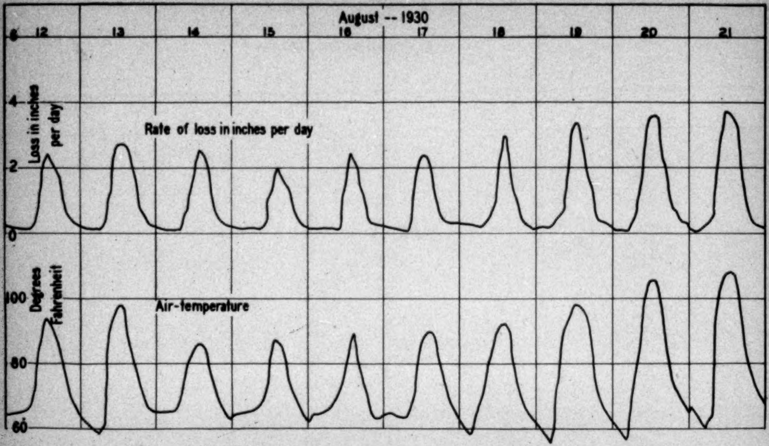


FIG. 5—EVAPORATION-TRANSPIRATION RATE AT ONTARIO WILLOW AND REED TANK AND ITS RELATION TO AIR-TEMPERATURE, BY C. A. TAYLOR BUREAU OF AGRICULTURAL ENGINEERING

transpiration is assumed to be practically zero during the early hours of the morning, say about 2 to 4 o'clock, then the rate of rise in the ground-water table during that period would be the rate of recharge. A tangent was then drawn to the curve at this point and marked r. This represents the rate of recharge of the ground-water table. If this rate were to continue throughout the 24 hours and there were no transpiration or other losses, the water-table would rise an amount equivalent to the distance marked 24r. Transpiration occurred, of course, and instead of rising, the ground-water table dropped the distance s during the day. Consequently, the transpiration-loss would be (24r + s) divided by the specific yield of the soil.

Although these results might provide a satisfactory estimate, they are subject to a certain error. This error is based on the assumption that the rate of recharge r continues as a straight line throughout the 24 hours. On Figure 6 is shown a typical record from a well maintained along the Santa Ana River. To the right of the record is a diagram of a typical well. The presence of the diurnal cycle in the ground-water table indicates that the ground-water is under a certain static head, and if there were no drain on the supply, the ground-water level would approach that head. Early in the season, when transpiration is practically nothing, the altitude of the ground-water table and the static head are the same or nearly the same. As indicated by the diagram, the increase of the transpiration-drain on the ground-water supply causes a cone of depression to form about the trees. As the water-table drops, the distance between the static head and the ground-water increases. This increase in difference of altitude causes an increase in the rate of recharge r, so that at the middle of the transpiration-season the rate of recharge will be a maximum. The record on this Figure clearly shows how the relatively small rate of recharge of June 17-19 increased to a maximum for July 30 to August 1 and then returned to a minimum between November 4 and 6.

Thus it is evident that the rate of recharge r is not a straight line but a curve which ranges from zero at the altitude of the static head to a maximum some distance below that point. By developing a relation between the ground-water altitude and the rate of recharge during the early morning hours, it was possible to develop the shape of this recharge-curve for this particular well. The maximum rate of recharge during August indicated that the static head was about 0.55 foot above the ground-water table for that month. Thus, it is possible that, if there had been no transpiration, the ground-water table would have been 0.55 foot higher.

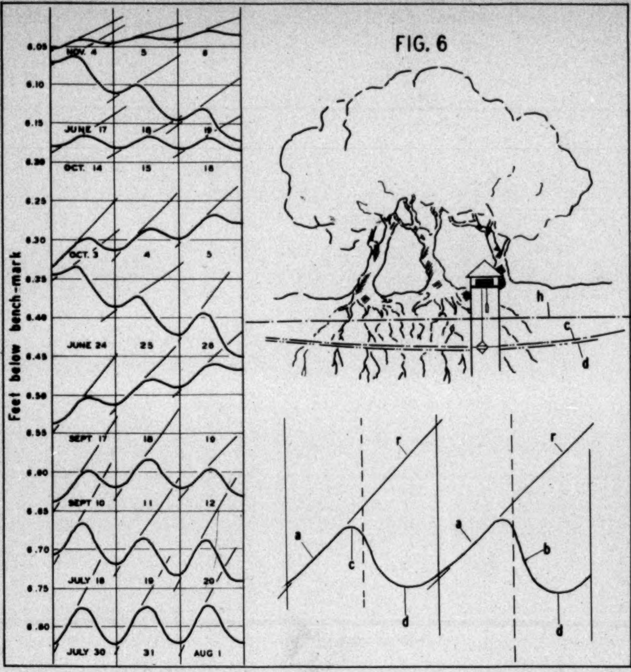


FIG. 6

The diurnal cycle as indicated by the ground-water table represents an accumulative curve showing the result of rates of inflow minus rates of transpiration. On the bottom of Figure 7 has been plotted the first derivative of this diurnal ground-water cycle. These rates have been expressed as the average for each hour and have been determined graphically. This curve represents the rate of change in the ground-water table, or the rate of inflow minus rate of transpiration.

It is reasonable to expect that between the hours of midnight and sunrise, the transpiration-losses would be at or near zero. During this period, then, the rate of change in the ground-water curve would equal the rate of inflow. In view of Figure 6 it is not unreasonable to expect that at the point c the rate of recharge will be a minimum and at point d the rate will be a maximum. It is impossible by this method to determine the actual rates of recharge during the transpiration-period. However, the rates for this period can be sketched in with sufficient accuracy to give hourly distribution of the transpiration-losses, which are indicated by the cross-hatched area on Figure 7. As indicated by this Figure, the measurable transpiration-losses start between 5 and 6 a.m., reach a maximum just before noon, and drop to zero shortly after 8 p.m. This agrees fairly closely with the work of Taylor at Ontario and the record from the Taylor evaporimeter.

Most of our streams flow through channels partly filled with recent alluvial deposits. A ground-water table is maintained in these deposits either by inflow from the tributary area or by inflow from the stream itself, or by both. In the first case the movement of the ground-water will be toward the stream, in the second the movement will be away from the stream, and in the

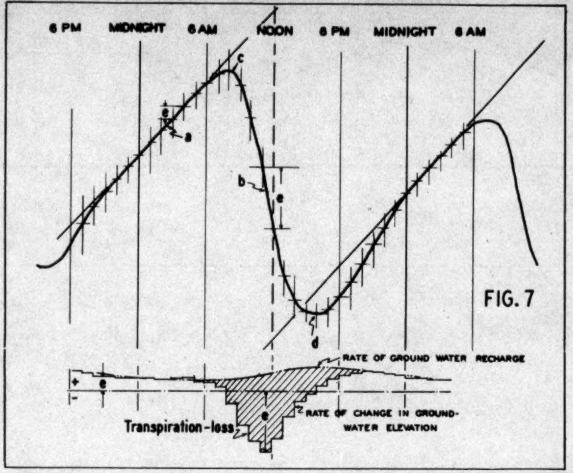

6 PM
MIDNIGHT
6 AM
NOON
6 PM
MIDNIGHT
6 AM
a
b
c
d
e
RATE OF GROUND WATER RECHARGE
RATE OF CHANGE IN GROUND-WATER ELEVATION
Transpiration-loss
+
-

FIG. 7

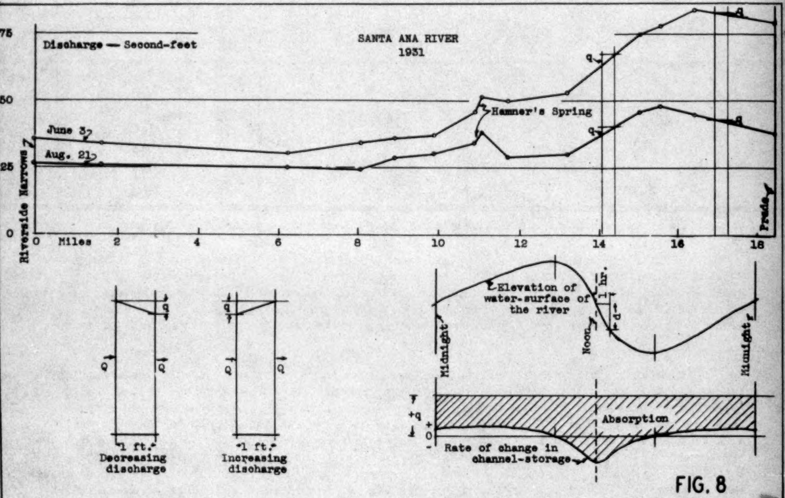

SANTA ANA RIVER
1931
Discharge — Second-feet
75
50
25
0
June 3
Aug. 21
Hamner's Spring
q
Riverside Narrows
Prado
Miles
0
2
4
6
8
10
12
14
16
18
Q
q
1 ft.
Decreasing discharge
Increasing discharge
Elevation of water-surface of the river
1 hr.
d
Midnight
Noon
Midnight
+q
+
0
-
Absorption
Rate of change in channel-storage
-q
Inflow

FIG. 8

third the movement may be in both directions. A riparian plant-life soon establishes itself and draws its water from this ground-water supply.

On the upper part of Figure 8 is a graph showing the discharge at a group of stations on the Santa Ana River for June 3 and August 31, 1931. These observations are the results of a series of simultaneous or nearly simultaneous current-meter measurements made by a group of field-parties from the United States Geological Survey and the Orange County Flood-Control District. These measurements were made between the hours of 8 and 10 a.m., during that part of the diurnal cycle in which the changes in channel-storage are small. As indicated by this graph certain sections of the River show a gain in discharge, while others show a loss. The gage-height records show a marked similarity in the diurnal cycle, both as to time and as to range of stage, notwithstanding the fact that in some sections the River lost discharge, while in others it gained.

Consider for the moment a reach of the stream one foot in length. Assume that this reach is located in a part of the stream in which the rate of flow diminishes progressively downstream. In this event the quantity of water entering this 1-foot reach in a unit of time (Q) will be greater than the quantity leaving it in the same time (Q_1). The difference between Q and Q_1, here called q, entered the reach but failed to leave it as surface-runoff. The tendency is for this quantity q to increase the channel-storage in the 1-foot reach.

In direct opposition to the effect of the increment q is stream-bed absorption. This absorption produces ground-water replenishment. At or about 10 a.m., the water-surface of the stream remains at a constant altitude for a short period, because at this time the quantity of water absorbed in a unit of time (a) exactly equals q in this 1-foot reach. After this period the rate of absorption increases rapidly, and the quantity of water absorbed in a unit of time (a) is equal to the quantity q plus a quantity withdrawn from channel-storage (s), thus lowering the level of the stream in the 1-foot reach. Late in the afternoon a and q again balance, and the water-surface remains constant for the time being. Then follows a period in which q exceeds a and channel-storage is increased. Thus we have the complete diurnal cycle.

It appears, at least to me, that the gage-height record of the stream is nothing more or less than an accumulative curve showing the relation between the positive factor q and the negative factor a. Under these conditions the following equations can be prepared

$$s = (q - a) \quad \text{or} \quad a = (q - s)$$

For any 1-foot reach of the stream the above equation is capable of solution, as follows: Let d = hourly change in altitude of the surface of the stream, in feet; b = width of stream, in feet; then, expressed in cubic feet a second, $a = [q - (db/3600)]$.

By means of this equation it is possible to establish the hourly variation in the rate of absorption. Assuming that q remains constant for the 24-hour period, then we have the rate of absorption as indicated graphically by the cross-hatched areas on Figure 8. This curve distinctly demonstrates that the gage-height record of the stream shows that maximum absorption occurs about noon and decreases to a minimum during the night.

In these reaches of the stream the rates of absorption are governed by the altitude of the ground-water table, which is in turn governed to a large degree by transpiration of the riparian plant-life. Thus maximum absorption should occur during the period of maximum transpiration, and minimum absorption during the period of minimum transpiration.

If the stream shows a progressive increase in rate of flow downstream, the reasoning will be very similar to that given for decreasing rate of flow. In this case the quantity of water (Q) entering the 1-foot reach is less than that leaving the reach (Q_1). The increase in rate of flow (q_2) has been taken from the reach. This q_2 becomes the negative part of the equation, in that it tends to reduce channel-storage (s). In direct opposition, the inflow or ground-water recharge (i) to the River tends to increase the channel-storage. Again the gage-height record of the stream becomes the accumulative curve of i (positive) and q (negative). Thus

$$s = (i - q) \quad \text{or} \quad i = (s + q) = (db/3600) + q$$

The second cross-hatched area on Figure 8 shows the inflow graphically. The inflow will be a minimum about noon and a maximum in the night. Here again the influence of transpiration is indicated. The inflow to the stream is governed by the condition of the ground-water supply. The heaviest demands by transpiration occur at noon; consequently the inflow to the River will then be a minimum. During the hours of little transpiration the inflow will be a maximum.

After a study of these two cross-hatched areas on Figure 8 it is only reasonable to expect that a stream will fluctuate in unison during the diurnal cycle at all points, much like a long pulsating reservoir. Take, for example, such a stream as the Santa Ana River. In some sections this stream shows an increase in discharge and in other sections a decrease in discharge. The graphs have indicated that for a losing stream the absorption will be a maximum at about noon. The same graphs show that on a gaining stream the inflow will be a minimum at noon. Thus on both a gaining and a losing stream the channel-storage is being depleted at its most rapid rate at noon. The same analysis can be applied to any other part of the diurnal cycle at all stations along the River. So it is not unreasonable to expect that the stream will fluctuate in unison or very nearly in unison at all points.

Owing to the frequent misuse of this diurnal cycle, it has been the purpose of this paper to demonstrate that the diurnal cycle found in the ground-water table and in the stream represents nothing more than an accumulative curve showing the difference between additions to and extractions from storage.

Furthermore, except for a few minor exceptions, it is the intent of this paper to question the assumption, often made, that this diurnal fluctuation progresses downstream. It is believed that there are now filed in the Los Angeles office of the United States Geological Survey sufficient data from southern California streams to prove that the diurnal cycle does not progress downstream.

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COMPARISON IN FLOWS OF CERTAIN SOUTHERN CALIFORNIA STREAMS WITH THAT OF THE COLORADO RIVER

J. B. Lippincott

The City of Los Angeles completed its Owens Valley Aqueduct in the year 1912 to bring in a new water-supply to that region. This aqueduct is some 250 miles in length and obtains its water from the Owens River which drains the eastern slope of the Sierra Nevada. This aqueduct is now being extended so as to also divert the water of the Mono Basin which collects its water from the eastern slope of the Sierra Nevada opposite the Yosemite Valley.

There is now being constructed the Colorado River Aqueduct of the Metropolitan Water-District to divert Colorado River water also to the Southern California Coastal Plain. The drainage-area of the Colorado above Laguna is 187,000 square miles. This drainage-basin extends northerly into the State of Wyoming. This northerly region is one where summer rains are frequent and where the routes of the major west to east winter storms may occur that do not reach as far to the south as the southern Sierra Nevadas, or southern California.

The interesting question arises as to whether the groups or cycles of wet years that occur in the Sierra Nevadas and in southern California will synchronize with those of the drainage-basin of the Colorado. It would be fortunate if the groups of dry years of our southern California streams do not coincide with similar groups of years in the drainage-basin of the Colorado. If so, the water-supply of the southern California coastal region would be better assured.

In order to determine the character of the flows of these groups of streams the hydrographic records were searched for as long a period as synchronous comparisons could be made. This period of record extends from 1904-05 to 1933-34, or 30 years. The season 1904-05 was at or near the beginning of a cycle of wet years which is now, we hope, reaching a close of the following group of dry years. A diagram (Fig. 1) has been made covering this period showing the annual flow of the Tuolumne and Owens rivers representing the Sierra streams, and the Colorado River. These fluctuations are shown in terms of percentage of the 30-year mean. A mass- or cumulative-flow diagram (Fig. 2) is also shown of the behavior of these three streams (first years shown are the beginning of a wet cycle). The following comparisons are made concerning the annual fluctuations:

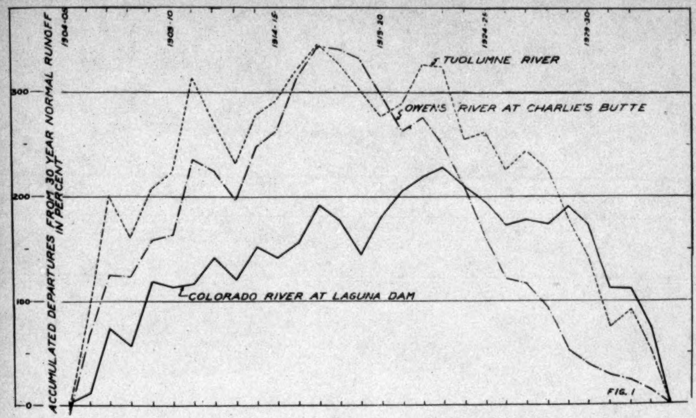

FIG. 1

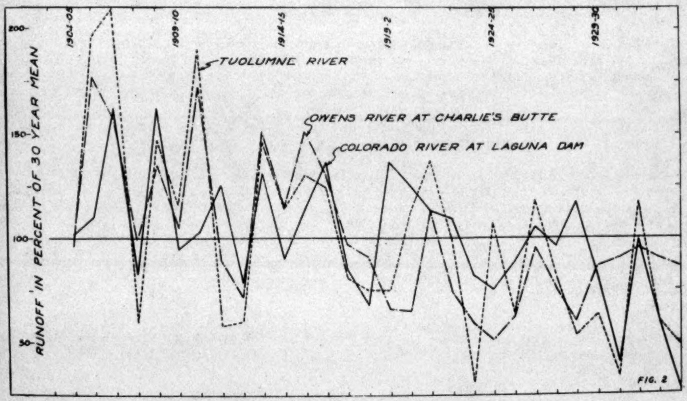

FIG. 2

Comparison Sierra streams with Colorado

Annual fluctuations for period 1904-05 to 1933-34

Tuolumne at LaGrange: Maximum 210 per cent in season of 1906-07; minimum 30 per cent in season of 1923-24

(Compensated for storage)

Owens at Charlie's Butte: Maximum 175 per cent in season of 1905-06; minimum 50 per cent in season of 1924-25

Colorado at Laguna Dam: Maximum 160 per cent in season of 1908-09; minimum 27 per cent in season of 1933-34

(Not compensated for storage which is small)

Peaks are: Tuolumne at 345 per cent in 1916-17; Owens at 343 per cent in 1916-17; Colorado at 230 per cent in 1922-23.

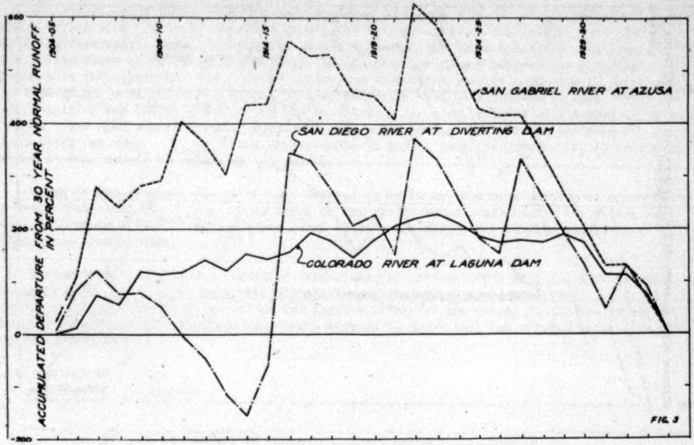

FIG. 3

Particularly the study of the mass-diagram indicates in a broad way that the wet and dry cycles in the area of the Sierra Nevada and the Colorado somewhat synchronize. This relationship, however, is not uniform or consistent. For instance, in the season 1909-10 the flow of the Tuolumne was 75 per cent of the normal, the Owens 65 per cent, and the Colorado 135 per cent, and again in the season 1928-29 the Tuolumne was 53 per cent, the Owens 60 per cent, and the Colorado 116 per cent. In the season 1930-31 the Owens River discharged 90 per cent and the Colorado River 40 per cent. These percentages refer to the relation of the annual flow to the 30-year mean.

The mass- or cumulative-flow diagram indicates an accumulated peak for the Tuolumne at 345 per cent in the season 1916-17, for the Owens 343 per cent in 1916-17, and for the Colorado 230 per cent in the season 1922-23. In other words, the cumulative peak of the Colorado for the wet cycle of years occurred six years later than that of the Sierra Nevada streams. This mass-diagram shows that the dry cycle in the Owens River Basin has continued since 1917, or for 17 years, while the dry cycle in the Colorado has continued in a marked degree since 1928-29, or for a period of five years. These diagrams indicate that there is greater necessity for a high ratio of storage-capacity to annual flow with our California streams than in the case of the Colorado.

A further comparison has been made between the performance of the San Gabriel and San Diego rivers in southern California and that of the Colorado. The following comparisons are obtained:

Southern California versus Colorado

Annual fluctuations for period 1904-05 to 1933-34

San Gabriel: Maximum 321 per cent in 1922; minimum 19 per cent in 1925
(No storage)

San Diego: Maximum 504 per cent in 1916; minimum 9 per cent in 1934
(Compensated for storage)

Colorado: Maximum 160 per cent in season 1908-09; minimum 27 per cent in season 1933-34

A mass-diagram (Fig. 3 is presented showing the accumulated percentage of flow of the San Gabriel, San Diego, and Colorado. It should be remembered that the first years shown on the diagram are broadly speaking for the beginning of a wet cycle.

The San Gabriel shows an accumulated peak of 628 per cent in the season 1921-22, the San Diego 372 per cent in the season 1921-22, and the Colorado 230 per cent in the season 1922-23. These diagrams also, and more, strongly indicate the necessity for a higher ratio of storage-capacity to mean annual flow in our southern California streams than in the case of the Colorado.

The Colorado River is shown on both of these comparisons to have a more consistent annual flow than either the streams of the Sierra Nevadas or those of southern California and is therefore of a more dependable character. Attention is called, however, to the fact that in the season 1933-34 the Colorado got down to its minimum record of 27 per cent of the 30-year mean.

In conclusion, it is found that, while there is a general tendency to synchronize in flow between the Colorado River and our California streams, this relationship is not closely followed and is of sufficient diversity so that it is valuable in connection with the stream-regulation by storage.

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EVAPORATION FROM WATER-SURFACES: STATUS OF PRESENT KNOWLEDGE AND NEED FOR FURTHER INVESTIGATIONS

N. W. Cummings

Five different methods have been proposed for estimating evaporation from lakes. These are: (1) The atmometer; (2) various designs of pan; (3) empirical equations embodying functions of wind, humidity, air-temperature, and water-temperature; (4) air-temperature alone; and (5) the following equations based on thermodynamics and molecular theory:

$$E = (I - B - S - C)/L(1 + R) \tag{1}$$

$$R = 0.46[(t_1 - t_2)/(p_1 - p_2)](P/760) \tag{2}$$

[The symbols in equations (1) and (2) are defined in section on "Symbols" at end of paper.]

It is hoped that in the planning of further investigations something can be accomplished by viewing the first four methods in the light of the last. Before doing this, however, it will be necessary to estimate the magnitudes of the quantities occurring in equation (1). For this purpose it will be convenient to use calories and Centigrade scale for temperatures, and it may be useful to remember that one-inch depth of evaporation corresponds to about 1500 calories per square cm of heat.

Now the amount of heat, I, coming from the Sun varies from 0 to 70 or 80 calories per hour per square cm. In other words, if all the heat coming from the Sun went into evaporation, it would produce a maximum rate of about 0.05 inch per hour. In 24 hours it would produce slightly less than half an inch at the times and places of greatest insolation. But this solar component is usually greater although it may sometimes be less than the amount of heat going into evaporation, and thus arises the necessity for the other quantities in the equation.

For example, B, the back-radiation to the sky, is always positive and varies from slightly more than zero to about 10 calories per hour per square cm. It may thus decrease by about 13 per cent, the amount of solar energy available for evaporation. Moreover, S, the heat stored in the water, may vary from about -10 to about +10 calories per hour per square cm, while C is usually negligible for a lake but may be about 10 calories per hour per square cm for a pan. The ratio R may for short times vary from -1 to +1, but for a 24-hour interval it is very seldom greater than 0.30 numerically and is frequently less than 0.20.

Let us examine the various methods in the light of these facts, remembering that the solar component is larger than any other single component, and frequently is larger than all the others combined. Consequently the readings of any atmometer or any pan must have a general tendency to increase as evaporation from a lake increases because both instruments certainly respond to solar radiation. However, the atmometer-bulb is usually made in the form of a sphere so that the solar heat it receives does not vary with solar altitude in a manner comparable to that of a pan or lake. Also, in the case of a pan or lake, it is the same identical surface which receives heat from the Sun and from the air. This is not true in the case of an atmometer. The variations in temperature of the surface of atmometer-bulb are greater than for a water-surface. This introduces great difficulty in dealing with R for the atmometer. On these theoretical grounds it seems rather unlikely that the atmometer will ever be reliable for estimating evaporation-losses from lakes, although it may be useful in the case of vegetation.

The insolation, I, is the same for a pan as for a lake if there is no shading, but B tends to be smaller for the pan and R more negative or less positive. Also, C is likely to represent a flow of heat into the pan. All these facts tend to make the depth from the pan greater than from the lake. For a pan the heat-storage, S, is usually small if the time-interval is 24 hours or more, but it may be numerically large in a lake in the spring or fall. In the fall, S may overbalance B, R, and C, so that at this time of year a lake may occasionally lose more than a pan. By insulating the pan, we eliminate the complication due to C.

Empirical equations are usually so formulated that the computed quantity tends to increase and decrease with solar radiation, so that it is in some degree correlated with observed evaporation.

The success of air-temperature alone can be explained by the fact that when the insolation is large, the temperature of the soil- and rock-surfaces must be high in order to discharge heat at the high rate. This in turn warms the air so that there is a correlation between air-temperature and evaporation.

Success of the various methods--I know of no data which show the success of the atmometer. Rohwer's work at Fort Collins (Tech. Bull. 271, U.S. Dept. Agric.) gives the best available basis for judging the success of methods (2), (3), and (4). It is easily found from his Table 16 that if 1.427 be taken as the correct ratio of the Weather Bureau pan to the reservoir, the average error in computing reservoir-loss is about nine per cent. The same Table shows that the average error for the reservoir as computed by Rohwer's empirical equation is 29.7 or approximately 30 per cent. The Table makes it possible to obtain the further information that the error resulting from the use of air-temperature alone is about 22 per cent.

If we make four assumptions, we may conclude that Rohwer's work on the Weather Bureau pan leaves nothing more to be done regarding the problem of evaporation. These assumptions are: (A) His 85-foot reservoir is truly representative of a lake; (B) his error is sufficiently small; (C) it is not worth while to find a more satisfactory pan; and (D) his coefficient may be regarded as holding for other times and places. Assumptions (A) and (D) are physical questions and are highly uncertain. Assumptions (B) and (C) are engineering questions. It is recommended, therefore, that the first thing to do is to get some reliable knowledge about real lakes. By the aid of the preceding equations (1) and (2) this can be done with any desired precision.

Symbols

The symbols used in equations (1) and (2) are defined as follows:

E is the depth of evaporation. It must be expressed as a certain number of units of depth for a given unit of time. In the applications of equation (1) that have thus far been made, the unit of depth has been the cm but it can just as well be the inch. The unit of time has been variously chosen as the minute, the hour, the day, the month, or the year, depending on circumstances.

I is the incoming radiation from the Sun and sky. The Monthly Weather Review reports it regularly for various stations in the United States, expressing it as calories per minute per square cm of horizontal surface. Like the other quantities in equation (1), it can easily be expressed in other units.

B is the back-radiation to the sky and is not to be confused with reflection. It is expressed in the same units as I.

S is the heat stored in a column of water during whatever interval of time is chosen for the other quantities. This column is supposed to have unit cross-sectional area and a length equal to the average depth of the lake. During the spring S is positive because the water is warming up, but in the fall S is usually negative because the water is then giving up its heat, partly to evaporation.

C represents a correction due to heat-leakage through the walls of a containing vessel, or heat carried through a lake with running water. It is expressed in the same units as I, B, and S.

L is the heat of vaporization of water. If E is to be expressed in cm of depth while the quantities in the numerator are in calories per square cm, then L must be in calories per cubic cm. At ordinary temperatures this is about 580. If we desire to express E in inches of depth, the numerical value of L is found by multiplying 580 by 2.54 which is the number of cm in an inch. This gives a result which in round numbers may be taken as 1500.

R has come to be known as Bowen's ratio. To understand it clearly, we must remember that heat is carried from a lake by two processes. In one, the energy goes off as the heat of vaporization of the water that is evaporated. In the other process, it is simply carried away as sensible heat just as it would be carried away from a non-volatile body. Of course, if the water is colder than air, then this latter process will bring heat to the lake instead of carrying it away. In any case, R is the ratio of the sensible heat to the latent heat; it may be calculated by the aid of equation (2). In equation (2) the t's represent temperatures, and the p's represent vapor-pressures. The subscript 1 refers to the water-surface while the subscript 2 refers to the air. Thus t_1 is the temperature of the water-surface, while t_2 is the temperature of the air; p_1 is the vapor-pressure of saturated vapor at the temperature of the water-surface, while p_2 is the partial pressure of whatever amount of water-vapor may happen to be in the air.

P is the barometric pressure expressed in mm of mercury.

Equations (1) and (2) together may be regarded as a rational means of interpreting pan-results when a thermally insulated pan is used. It is well known that no pan gives the same depth of evaporation as a nearby large body of water, but these equations not only explain qualitatively the reasons for the difference, but they also enable us to compute quantitatively the magnitude of the difference.

For further explanations, see "Results of evaporation-studies conducted at the Scripps Institution of Oceanography and the California Institute of Technology" by G. F. McEwen (Bull. Scripps Inst. Oceanogr., Tech. Ser., v. 2, No. 11, pp. 401-415, 1930), "Evaporation from lakes" by N. W. Cummings and Burt Richardson (Phys. Rev., v. 30, pp. 527-534, 1927), and "The ratio of heat losses by conduction and by evaporation from any water surface" by I. S. Bowen (Phys. Rev., v. 27, pp. 779-787, 1927).

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DISCUSSION OF "EVAPORATION FROM WATER-SURFACES: STATUS OF PRESENT KNOWLEDGE AND NEED FOR FURTHER INVESTIGATION"

A. A. Young

The title of this paper raises the questions of what is the engineer's knowledge of evaporation and what beneficial use can be made of that knowledge. Once these questions are answered an outline of further investigation may be suggested.

The history of evaporation-studies in the West began more than half a century ago. The earliest published records in the Los Angeles Area were obtained at Pomona where measurements were made under the direction of the Division of Irrigation Investigations (now the Division of Irrigation), United States Department of Agriculture, between 1903 to 1905 (Samuel Fortier, Evaporation-losses in irrigation- and water-requirements of crops, U. S. Dept. Agric., Office Experiment Stations, Bull. 177, 1907).

Following those measurements the United States Weather Bureau stood sponsor for an extensive investigation at the Salton Sea from 1907 to 1910 (Studies of the phenomena of the evaporation of water over lakes and reservoirs, Mon. Weath. Rev., v. 35, 1907, v. 36, 1908, v. 38, 1910),

A few years later the Division of Irrigation Investigations undertook the important study at Denver (Evaporation from surfaces of water and river-bed materials, J. Agric. Res., v. 10, No. 5, 1917), which developed the first satisfactory coefficients for reducing pan-evaporation to reservoir-equivalents. In order to check these coefficients a further study was begun at Fort Collins, Colorado, by the Division of Irrigation, and a report was published in 1931 (Evaporation from free water-surfaces, U. S. Dept. Agric., Tech. Bull. No. 271, 1931).

In southern California, the Division has been conducting further studies since 1928 (Water-losses under natural conditions from wet areas in southern California, Calif. State Bull. No. 44). Thus, studies of evaporation-problems have been carried on by the Division almost continuously for a period of over 30 years.

The investigation at Denver (J. Agric. Res., v. 10, No. 5, 1917) in 1915 was pioneer work. Little, if any, knowledge existed as to coefficients to be applied to evaporation from pans to determine reservoir-losses. The coefficient of greatest importance to engineers because of its wide-spread opportunity for use was 0.67 to be applied to Weather Bureau pans. At Fort Collins (U. S. Dept. Agric., Tech. Bull. No. 271, 1931) better opportunity, afforded through measurements from an 85-foot diameter reservoir, developed a coefficient of 0.70 instead of 0.67. This value has since been recommended for general use by the Sub-Committee on Evaporation of the Special Committee on Irrigation-Hydraulics of the American Society of Civil Engineers (Standard equipment for evaporation-stations, Final Report of Sub-Committee on Evaporation of the Special Committee on Irrigation-Hydraulics, Proc. Amer. Soc. C. E., February 1933). It now has wide-spread use throughout the West for reduction of evaporation from a Weather Bureau pan to reservoir-values.

As the terms ratio and coefficient used in this paper may appear confusing to some, it seems proper to make some distinction. The term "ratio" is here used only when comparing evaporation from any two pans. These may be of the same or of different types. It is confined to station-investigations. A "coefficient" is a ratio used for reduction of evaporation from a pan to reservoir- or lake-equivalents. It is the final result of an evaporation-investigation.

Two evaporation-stations now used by the Division of Irrigation in southern California are at Baldwin Park and at Fullerton. Experiments at both are conducted in cooperation with other agencies. Records for Baldwin Park are available since July 1932, but records for Fullerton exist only through 1935. The largest evaporation-pan at Baldwin Park is six feet in diameter; that at Fullerton is 12 feet. Both are of the Bureau of Agricultural Engineering type, three feet in depth.

Sleight (J. Agric. Res., v. 10, No. 5, 1917), at Denver, comparing evaporation from a number of similar pans, differing only in diameter, concluded that the loss from a 12-foot pan was very nearly equal to that from an open reservoir. This assumption was later supported by Rohwer (U. S. Dept. Agric., Tech. Bull. No. 271, 1931) at Fort Collins in measuring evaporation from a reservoir. For this reason the 12-foot pan was adopted as a basis of study at the Fullerton station.

The California investigation is, in a limited way, a repetition of Sleight's work but is carried on under different climatic conditions. Freezing weather necessarily limited the investigations in Colorado to eight or nine months of each year. In California, as elsewhere on the Pacific Coast and in the Southwest, evaporation is continuous throughout the year. It is becoming increasingly apparent that the longer evaporating period has some effect upon the resultant ratios. At a number of places where it has been possible to obtain monthly ratios of evaporation it has been found that those for the summer months are above the mean value for the year, while those for the winter are below the mean. The result is that the yearly mean ratio of evaporation is less than the mean for the shorter period, April to November, inclusive, which are the Colorado months of evaporation. In itself, the difference--possibly three or four per cent--may not be important when averaged over a year's time, but when combined with other factors it should be given consideration.

In most cases evaporation-losses from reservoirs are computed on a yearly basis but under certain conditions shorter periods must of necessity be considered. In southern California, flood-control reservoirs are most in use during the rainy winter season. Landowners below this type of storage are entitled to definite portions of the normal stream-flow and evaporation-losses from the reservoir must be considered in the light of water-requirements. For this purpose the yearly mean coefficient cannot be used as it does not apply to the particular winter months when the flood-water is in storage. The limited investigations to date seem to indicate that a winter-coefficient about ten per cent less than the yearly mean is more likely to be correct.

Giving due consideration to existing differences in climate between Colorado and southern California, it is not surprising that there are found corresponding differences in evaporation-coefficients. Comparison of records from the 12-foot pan and the Weather Bureau pan at Fullerton for 1935 shows a ratio of 0.77 or 11 per cent greater than the 0.70 adopted by the Sub-Committee on Evaporation (Proc. Amer. Soc. C. E., February 1933). If the months April to November, inclusive, corresponding to the evaporation-period in Colorado, are considered, the ratio is increased to 0.79. This difference, in itself, shows the value of repeating the Colorado studies, indicating, as it does, that coefficients determined under certain climatic conditions cannot be entirely relied upon under dissimilar conditions.

It must be understood, however, that the Fullerton figures are only for the first year and are not final. Previous experience has shown that a single year's records do not make as accurate a ratio as those of a longer period. Measurements for three and one-half years at Baldwin Park still show slightly changing ratios with additional records. It is expected that experiments at the Fullerton station will be continued for several years to establish reliable coefficients for southern California conditions.

Need for future investigations--That differences in climate affect coefficients has been shown in the comparison of the Colorado Weather Bureau pan-coefficient of 0.70 and the one of 0.79 at the Fullerton station. This is attributable largely to difference in temperatures, wind-movements, humidity, and length of evaporating season. Writers have often pointed out that coefficients are correct only for the exact climatic conditions for which they were determined. The two Colorado stations have the same climate and the Weather Bureau pan-coefficient was the same for each locality. Likewise, in California the two stations have the same general climate and, as far as investigations have continued, the principal ratios agree.

That either ratio or coefficient may differ considerably at points within a few miles is shown by comparison of records for Baldwin Park with those obtained by the Pasadena Water-Department at the site of the Morris Reservoir in the San Gabriel Canyon. The station, at this time, was located in the canyon-bottom a short distance above the site of the Dam. It contained a Weather Bureau pan and one of the Bureau of Agricultural Engineering type, six feet in diameter by three feet deep. The distance between Baldwin Park and Morris Reservoir is roughly about ten miles. San Gabriel Canyon is a narrow, winding opening in the San Gabriel Mountains which rise sharply above the stream-bed to a height of more than 1000 feet. The station was thus surrounded by mountains, a topography entirely different from the level plain at Baldwin Park.

The effect of topography is noticeable when records for the two stations are compared. In a period of 17 months evaporation from the Weather Bureau pan at Morris Reservoir was 23 inches greater than at Baldwin Park, and the resultant ratio of evaporation from the Weather Bureau pan to the 6-foot pan was 14 per cent greater. This point is emphasized to show the necessity of careful investigation before a coefficient is adopted for use at places situated otherwise than the station at which the coefficient was developed. It is proof that coefficients are correct only under the original conditions for which they were determined.

Mountain-reservoirs are often located in narrow, crooked canyons that have been former stream-channels. All parts of the reservoir-surface are not subject to the same effects of Sun, wind, air, or water-temperatures. A limited investigation has disclosed that these factors vary considerably at different points along the shore-line. Wind-movement is strong at exposed points of land extending into the reservoir while there is little wind in protected bays. Both air- and water-surface temperatures are greater in quiet areas subject to sunshine than in other areas shaded by mountain-spurs. Humidity is far from being a constant value at different points on the reservoir-surface, sometimes varying as much as 100 per cent. As far as evaporation is concerned it seems probable that reservoirs have characteristics aside from those caused by climatic differences. In this connection it should be pointed out that Rohwer's investigation (U. S. Dept. Agric., Tech. Bull. No. 271, 1931) was based upon an 85-foot circular reservoir in open country and was therefore not affected by conditions peculiar to mountain-canyons. All these facts point to the need for actual investigation of reservoirs carried on in conjunction with present investigations at stations.

No attempt at such a comparison has been made, although good opportunity for a mountain-study exists at Lake Arrowhead in the San Bernardino Mountains. Such work would not only afford a study of the evaporation-losses from lakes of much-needed water but would help to tie in the work at Fullerton with previous work in Colorado. The elevation of Lake Arrowhead is 5100 feet, nearly the same as at Fort Collins and Denver, and although winter conditions are not as severe as in Colorado, there is a short period of freezing weather which does not occur at the lower stations. A comparison of results under the two conditions would be of value.

With determination of useful coefficients,the aim of investigations at stations, it is important to use the type of pan giving the best results. Up to the present various sizes and types have been used and ratios established between them. So far, such studies have not included insulated pans although there is growing evidence that such pans should be investigated. Little, if anything, is known about coefficients for insulated pans. The question arises as to what is the best size and shape, what insulation to use, and what depth of water should be maintained. The effect of insulation is best studied from insulated pans of certain design. From an engineer's point of view another design may seem more suitable for the end desired. For determination of reduction-coefficients the best pan is one having evaporation nearest equal to that from a larger body of water, that is, one approaching unity.

If an insulated pan can be designed to give a high coefficient it can be of small diameter, easily installed, and operated with a minimum water-supply. This would make it suitable for mountain-use. Once a coefficient were established, this type of pan could be used at every reservoir-site and fairly accurate evaporation, for that particular reservoir, computed from pan-measurements. For this purpose it seems probable that insulation should not only be confined to the outside and bottom but should also protect the inner rim at and above the water-surface, thus preventing accelerated evaporation at the water-line. To obtain such insulation presents some difficulty as it must not only insulate the rim but it must be fairly non-absorbent to prevent capillary spread of the evaporating area. At first glance the two conditions seem contradictory and some compromise may be necessary.

The previous suggestions have been made for the purpose of increasing interest in evaporation-studies in mountain-areas where the majority of reservoirs are found. In addition it is suggested that records of evaporation be made useful to those interested through collection, compilation, and publication of all available records. The majority will be in the Western States. Fragmentary records now exist in various publications but there can be no question that many more are buried in files of engineers and water-companies. The writer has personal knowledge of one such record in California, continuing uninterruptedly for the past 12 or 15 years without publication. Such records are of no value except to the owner. If every available record of evaporation, together with all possible data on air- and water-temperatures, humidity, wind-movement, rainfall, description of pans, location, and elevation of the station, were brought together in a single publication, it would be of vast benefit to western engineers and research-workers.

In conclusion, it should be understood that past and present investigations in evaporation are preliminary to additional studies which should be undertaken at lakes and reservoirs. It would not be surprising if each lake and reservoir had individual characteristics depending upon shape and size of the water-surface, depth of water, nature of surrounding topography, type of adjoining vegetation, as well as different climatic factors. If this be true, coefficients developed at evaporation-stations can never be more than closely approximate when applied to reservoirs. The error may be of small importance both in amount and value of water, but, on the other hand, it may sometimes be serious. It is only through continued investigations that these questions can be answered satisfactorily.

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CHANGES IN THE COMPOSITION OF GROUND-WATERS RESULTANT TO ANAEROBIC SULFATE DECOMPOSITION AND THE ATTENDANT PRECIPITATION OF CALCIUM AND MAGNESIUM

Frank M. Eaton

In a paper on the quality of ground-waters [see 4 of "References" at end of paper], published in February 1935, I pointed to the fact that many of the deep wells along the axis of the San Joaquin Valley of California produced waters that contained very little sulfate (Table 1). These deep waters are sometimes relatively saline and yet many of them contain less sulfate than the surface-waters that now enter the Valley. The evidence, though indirect, supported the conclusion that these waters had been altered chemically after having entered the ground. The most logical conclusion was that sulfate had been lost as a result of anaerobic decomposition.

In the original paper no emphasis was placed on an associated observation of equal importance. Many of these saline low-sulfate waters contain little calcium or magnesium. The percentage of sodium (see foot-note 2, Table 1) was customarily found to be high in the waters in which sulfate decomposition was believed to have occurred.

As a general characteristic, the waters along the greater part of the west side of the San Joaquin Valley contain relatively high concentrations of sulfate, and in these waters calcium and magnesium not infrequently constitute a substantial proportion of the total bases. The coastal mountains, comprised as they are of soft serpentines, shales, and sandstones, are rich in gypsum and other relatively soluble minerals. Several examples of waters from the west side of the Valley are given in Table 2.

The streams rising in the Sierra are much larger than those from the coastal mountains and they contribute a far greater proportion of the total water-supply that enters the valley-floor. The surface- and ground-waters of the east side of the Valley, as might be expected, have only a moderate mineral content (Table 3). Bicarbonate is usually the dominant anion. The Sierra is largely comprised of resistant granites and metamorphic rocks of low solubility.

Table 1--(A) Examples of low-sulfate waters from deep wells along axis of San Joaquin Valley; (B) shallow well in the bed of Tulare Lake; and (C) old analyses of Tulare Lake waters

Type and location	Location[1]	Depth feet	K × 10^5 at 25°C	Milligram-equivalents per liter						Per cent Na[2]
				Ca	Mg	Na	HCO_3	SO_4	Cl	
(A) Low-sulfate well waters										
Deep wells in Tulare Lake bed	24- 3	1800	171	1.77	1.20	15.32	10.60	0.09	7.60	84
	24- 4	2100	137	1.54	1.03	11.08	6.30	T[x]	7.35	81
	24- 5	1951	112	1.28	0.81	8.61	5.30	T[x]	5.40	80
	24- 6	1950	243	2.31	1.28	21.16	10.00	0.15	14.60	85
	24- 7	1800	124	1.43	0.48	10.41	5.60	0.02	6.70	85
Adjacent deep wells	25- 5	1900	92.4	0.97	0.56	7.42	4.40	T[x]	4.55	83
	25-12	835	1055	3.65	12.90	96.84	28.10	0.29	85.00	85
	25-13	830	82.8	0.63	0.68	7.04	5.40	T[x]	2.95	84
Gas well at Lodi	3- 4	1900	176	4.06	2.13	9.21	1.05	T[x]	14.35	60
Gas well at Stockton	3-10	3300	1256	43.42	11.72	67.55	1.15	0.04	121.50	55
(B) Shallow well, bed Tulare Lake	24-18	150	524	5.90	13.30	42.09	27.00	2.14	22.15	69
(C) Old analyses, waters Tulare Lake	(January 1880)			1.00	1.96	20.55	12.04	4.79	6.65	87
	(Spring 1880)			0.85	1.72	20.00	12.37	4.23	5.91	89
	(February 1889)			0.70	1.07	79.59	31.88	21.25	28.00	98

[1] Location by quadrangle and number as of U. S. Dept. Agric. Tech. Bull. 448.

[2] Sodium as per cent of total milligram-equivalents of Ca, Mg, and Na.

[x] T = trace.

Descriptions of samples listed in Table 1

Location 24-3: Kings County Development Co. Well; near northwest corner sec. 18, T.21S, R.20E; depth, 1800 feet; running lift, 160 feet; temperature, 90° F.

Location 24-4: Kings County Development Co. Well; near northeast corner sec. 18, T.21S, R.20E;. depth, 2100 feet; casing perforated below 1200 feet; running lift, 200 feet; discharge, 4.5 cubic feet per second; warm and gas.

Location 24-5: Nick Weis Well; near center sec.23, T.21S, R.20E; depth, 1951 feet; perforated below 955 feet.

Location 24-6: Kings County Development Co. Well; near northwest corner sec.30, T.21S, R.20E; depth, 1950 feet; discharge, 4 cubic feet per second; temperature, 99° F.

Location 24-7: A. H. Wolfsen Well; north center sec.36, T.21S, R.20E; depth, 1800 feet; discharge, 3.6 cubic feet per second; temperature, 91° F.

Location 25-5: Post Card Ranch, Well No. 1; near northeast corner sec.21, T.22S, R.22E; depth, 2300 feet; casing perforated below 1500 feet; report water produced by stratum at 1800 feet; temperature, 90° F.

Location 25-12: Deep well west of La Hacienda Ranch; southwest 1/4 sec.19, T.24S, R.22E; depth, 835 feet; static level, 12 feet; 12-inch casing; perforations thought by stockman to be below 500 feet; operated by small rotary pump to supply cattle; drilled in 1929.

Location 25-13: La Hacienda Ranch, well at headquarters; near center sec.17, T.24S, R.22E; depth, 830 feet; upper perforations at 400 feet; 9-5/8-inch casing; used for stock and domestic purposes.

Location 3-4: Lodi Municipal Well; used for bath house; depth, 1900 feet; temperature, 68° F; high gas-content; formerly flowing, now operated by small pump.

Location 3-10: Gas well, Wilson Way and Minor Avenue; depth, 3300 feet; temperature, 96° F; serves Olympic Baths.

Location 24-18: Gates Ranch, shallow well; near southeast corner sec.36, T.22S, R.21E; depth, about 150 feet; water used only for washing, etc.; gas from the well is trapped and used for gas ranges.

Old analyses of Tulare Lake waters; California University Agricultural Experiment Station report of 1890; recomputed by Dole (7) from hypothetical combinations to parts per million

Table 2--Examples of high-sulfate waters west of the axis of the San Joaquin Valley

Station	Location[1]	K x 10^5 at 25°C	Milligram-equivalents per liter						Per cent Na[2]
			Ca	Mg	Na	HCO_3	SO_4	Cl	
Mountain House Well	6-9	207	3.10	5.61	12.80	6.00	5.72	9.65	60
Panoche Creek	14-5	279	7.11	9.36	15.83	5.20	22.25	4.85	49
Silver Creek	14-6	806	19.51	42.37	47.54	5.70	88.82	14.90	43
Halfway Station Well	18-1	178	5.67	10.26	5.25	3.95	14.78	2.45	25
Associated Oil Co. Well	18-3	208	2.61	9.81	11.16	5.95	13.88	3.75	47
F. G. Ladd Well	19-7	330	12.51	12.11	12.76	1.90	31.23	4.25	34
Crescent Meat Co. Well	22-1	506	13.33	7.25	41.18	6.20	41.36	14.20	66
T. Curvi Well	22-2	278	8.33	9.54	14.98	2.90	24.85	5.10	46
Well near Zapata Creek	23-6	359	21.85	17.71	9.55	5.00	42.46	1.65	19
Adobe spring	34-2	188	9.45	8.37	4.50	4.10	16.67	1.55	20

[1] Location by quadrangle and number as of U. S. Dept. Agric. Tech. Bull. 448.

[2] Sodium as per cent of total milligram-equivalents of Ca, Mg, and Na.

Descriptions of samples listed in Table 2

Location 6-9: Mountain House Well; near center south 1/2 sec.18, T.2S, R.4E; a shallow well with brick casing; static level, about 12 feet; supplies service-station.

Location 14-5: Panoche Creek; near center west 1/2 sec.27, T.15S, R.11E; discharge, approximately 2 cubic feet per second.

Location 14-6: Silver Creek, northwest 1/4 sec.32, T.15S, R.12E; at P.G. and E. gas-line crossing; discharge at time of sample approximately 0.03 cubic foot per second.

Location 18-1: Halfway Station Well, Associated Pipe-Line Co.; near northwest corner sec.7, T.17S, R.14E; depth, 700 feet; 295 feet to water.

Location 18-3: Associated Oil Co., shallow domestic well; Los Gatos Creek Delta; probably sec.18, T.20S, R.15E.

Location 19-7: F. G. Ladd, irrigation-well; northwest 1/4 sec.12, T.18S, R.16E; depth, 150 feet.

Location 22-1: Crescent Meat Co., shallow well near Waltham Creek; near center west 1/2 sec.8, T.21S, R.15E.

Location 22-2: T. Curvi, shallow domestic well beside Jacalitos Creek; sec.14, T.21S, R.15E; depth, 15 feet.

Location 23-6: Well near Zapata Creek, drilled to supply rotary oil rig; northeast 1/4 sec.18, T.22S, R.16E; depth, 512 feet.

Location 34-2: Adobe Spring, San Emigdio Creek, in unsurveyed area; position corresponds to southwest corner sec.1, T.10N, R.22W; discharge, 0.15 cubic foot per second.

Table 3--Stream-waters from the high Sierra along the east side of the San Joaquin Valley

Station	Location[1]	K x 10^5 at 25°C	Milligram-equivalents per liter						Per cent Na[2]
			Ca	Mg	Na	HCO_3	SO_4	Cl	
Mokelumne River	3-2	6.41	0.30	0.11	0.22	0.55	0.03	0.05	35
Stanislaus River	7-4	23.0	1.05	0.75	0.41	1.95	0.04	0.15	19
Merced River	9-6	16.2	0.61	0.22	0.70	1.22	0.16	0.15	46
Columbia Canal	15-6	5.29	0.32	0.09	0.12	0.30	0.08	0.15	23
Kings River (average of 2)	21-1	11.0	0.51	0.06	0.45	0.79	0.16	0.10	46
Kern River (average of 3)	32-1	10.5	0.53	0.05	0.57	0.83	0.17	0.15	50

[1] Location by quadrangle and number as of U. S. Dept. Agric. Tech. Bull. 448.

[2] Sodium as per cent of total milligram-equivalents of Ca, Mg, and Na.

Descriptions of samples listed in Table 3

Location 3-2: Mokelumne River, near Lodi.

Location 7-4: Stanislaus River, south of Ripon.

Location 9-6: Merced River, near Livingston.

Location 15-6: Columbia Canal; diverted from San Joaquin River above mouth of Fresno Slough.

Location 21-1: Kings River, between Traver and Kingsburg.

Location 32-1: Kern River, Bakersfield; sampled at heading of East Side Canal.

The deeper ground-waters along the axis of the Valley (Table 1) are commonly distinct from the surface- and ground-waters along the two sides of the valley-floor. Dole [7] in considering these relationships concluded that the quality of the ground-waters of the Valley, specifically their sulfate-content, provided an index to the source of the alluvium from which they were drawn. This conclusion, though not without interest, does not account for the chemical nature of the axial waters.

That the surface-waters that entered the Valley at an earlier period, during the building up of the valley-floor, contained less sulfate than the waters that now enter the Valley seems improbable. The sulfate-content of the present waters from the Sierra is low but sulfate nevertheless constitutes a substantial proportion of the total salinity. Waters that accumulated in Tulare Lake (Table 1) likewise contained substantial quantities of sulfate.

Though it does not appear from the literature that sulfate-reduction by anaerobic bacteria in deep potable waters has been demonstrated, the reaction is a common one that has received extensive consideration under the other conditions [1, 2, 5, 6]. Equations of the following type have been postulated to explain the reaction:

(1) $CaSO_4 + CH_4 = CaCO_3 + H_2S + H_2O$ (3) $Na_2SO_4 + CH_4 = Na_2CO_3 + H_2S + H_2O$

(2) $MgSO_4 + CH_4 = MgCO_3 + H_2S + H_2O$ (4) $CaSO_4 + 2C = CaS + 2CO_2$

The presence of organic matter is essential to sulfate-reduction by bacteria. The writer cannot recall that combustible gases were present in any of the sulfate-waters from wells along the west side of the Valley but such gases (possibly methane) are of common occurrence in wells in the lake-bottom and elsewhere along the axis of the Valley. A more detailed discussion of the evidence pointing to the conclusion that these deep waters have been altered was presented in the earlier paper and accordingly it may be omitted here.

Notwithstanding the conclusion that bacterial activity probably accounts for these alterations, it is appropriate to point out that free-energy calculations as made by L. V. Wilcox of this Laboratory indicate that these reactions could be expected to proceed in the direction of completion without the aid of organisms. Rogers [8] did not consider bacteria in endeavoring to account for the composition of oil-field waters.

Should the presence of living sulfate-reducing bacteria in these waters be demonstrated by appropriate bacteriological procedures, such fact would establish the major cause of the changes, but negative results from such tests would scarcely eliminate bacteria as the cause. These deep waters, lying as they do far below sea-level, have been impounded for many years and the changes that brought about their present chemical make-up may have occurred long ago. Bacteria, once active, might no longer be present. The shallow well at location 24-18 (Table 1) emits much gas. The water contained 2.14 milligram-equivalents of sulfate, which is less than that shown in the lake-water analyses. In this well active reduction may be in process, and if living bacteria are responsible for the reaction they should be found in this well.

The concentrations of calcium and magnesium were notably low in the majority of the waters in which a loss of sulfate was evident. The precipitation of these constituents should accompany the loss of sulfate, since carbonates are an end product of the reactions. Calcium as calcium carbonate has a solubility in pure solution of less than 0.5 milligram-equivalents per liter and magnesium carbonate is soluble to the extent of about three milligram-equivalents per liter. Calcium and magnesium are prominent in the Lodi and Stockton gas-well analyses, but this may well be the case since their precipitation would proceed only to the point at which the sulfate was exhausted. A trace and 0.04 milligram-equivalents of sulfate, respectively, were found in these waters.

Waters of the type here discussed are not limited to the San Joaquin Valley. They are found in many places. Similar waters are produced from farm wells in Nevada, not far from Carson Sink, and they are found in Colorado and Montana. The brown waters from deep wells near Long Beach are notably low in sulfate and in calcium and magnesium.

The loss of sulfate from these waters is of practical as well as academic interest. On the basis of investigations by the writer that have been published only in part [4], concentrations of sulfate above the few milligram-equivalents essential to normal growth of plants are to be regarded as toxic and undesirable. If no other considerations were involved the loss of sulfate should be looked upon as advantageous. With the loss of sulfate there is, however, the associated loss of calcium and magnesium. In other words, the per cent sodium is increased.

Viewed from the standpoint of the permanency of our irrigation-enterprises, the per cent sodium of natural waters is a highly important concept [4]. Waters in which sodium is the predominant ion are not satisfactory irrigation-waters. The sodium of the water tends to displace the absorbed calcium and magnesium of the soil. Waters with high percentages of sodium ultimately bring about changes in the soil that are not conducive to the growth of plants. Soils containing much absorbed sodium tend to become deflocculated and hard, and difficult to work.

Furthermore, they tend to become impervious to the movement of water. When irrigation-waters do not penetrate beyond the root-zone to promote leaching, the accumulation of salt in the soil-solution becomes rapid. When penetration into the root-zone is retarded, the soil's function as a storage-reservoir for water is restricted.

It is not to be concluded that the occurrence of high-sodium waters is confined to those originating in deep wells in which there is evidence of sulfate reduction. The reaction may be far more common than we suppose.

In the San Joaquin Valley [4], 54 per cent of the well-waters analyzed contained more than 50 per cent of sodium and 31 per cent of them contained more than 70 per cent of sodium.

In the South Coastal Basin of California [3], 20 per cent of the 1144 well-samples of which complete analyses were made contained more than 50 per cent sodium and eight per cent of them more than 70 per cent sodium.

The drainage-waters from irrigation-projects are always more saline than the irrigation-water and quite regularly they have higher sodium percentages. Some calcium and magnesium are precipitated in the soil as carbonates. Calcium sulfate may likewise be precipitated as a result of concentration by evaporation and transpiration, but the solubility of calcium sulfate in the soil-solution is in the order of 30 milligram-equivalents per liter.

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A STUDY OF HIGH-VELOCITY FLOW IN CURVED CHANNELS OF RECTANGULAR CROSS-SECTION

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In the following paper is given a short and general outline of certain hydraulic research, which has been carried on at the Hydraulic Structures Laboratory of the California Institute of Technology under the direction of Professor R. T. Knapp for the past half year. This study was made possible through the cooperation of the Los Angeles County Flood-Control District, the Chief Engineer, C. H. Howell, and members of his technical staff. The problems are of a nature scarcely treated so far in hydraulic literature. They arose in connection with the building and design of concrete-lined flood-channels of rectangular cross-section, which are supposed to carry the flood-waters of the so-called Foothill Area north of Glendale safely down through the settled districts of La Canada, La Crescenta, and Glendale to the Los Angeles River. The Los Angeles County Flood-Control District is in charge of this work and the engineers responsible for the design of these flood-channels found themselves faced with the following problems.

How will water flowing at velocities from 30 to 60 feet per second react to changes in direction; how should these changes of direction be made; what radius of curvature is permissible

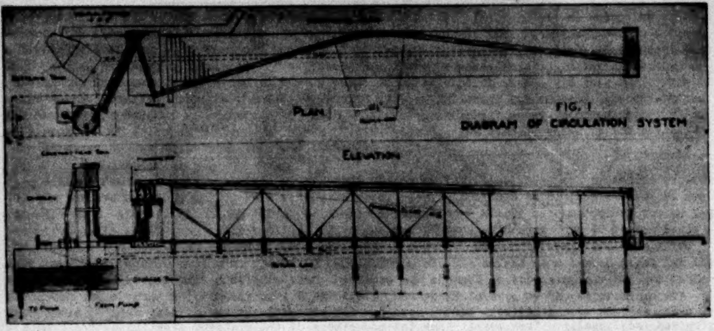


FIG. 1
DIAGRAM OF CIRCULATION SYSTEM

for those channels, how much free-board should be provided for the yet unknown superelevations in the curves; further, what disturbances will be caused in the straight sections below the curves, and how soon will these disturbances die out?

It was believed by the engineers in charge and by the staff of the Hydraulic Structures Laboratory of the California Institute of Technology that model-studies would supply this information. The governing forces are inertia- and gravity-forces and therefore dynamic similarity can be obtained between model and prototype. Since, however, the conditions to be met in the field vary a great deal, it seemed not suitable to investigate individual curves, but instead a comprehensive research-program was laid out to cover the entire range of conditions. General relations were ultimately to be looked for rather than individual solutions. The experimental set-up was designed and constructed as seen in Figure 1 to correspond to the analysis of conditions and variables to be represented. A closed circuit was provided, the water was pumped to a constant-head tank, from where it is drawn to the flume through a pipe-system consisting of parallel lines of 10-inch, 6-inch, and 3-inch pipe. Corresponding Venturi meters measure the discharge which can conveniently be varied from low to high. The water enters the flume on the tilting platform through a rectangular nozzle with an adjustable tongue. With the aid of this adjustment it is possible to give the water any desired velocity and have it enter the testing flume at the velocity of uniform flow for all the desired hydraulic conditions, such as varying depths and slopes. A long channel of approach, necessary otherwise to accelerate the water from zero-velocity in a stilling-basin to the high velocities desired, was thereby avoided. At the downstream-end of the flume the water is discharged into a collection-basin and returned through an underground concrete-pipe to a settling-tank and finally to the storage-reservoir.

The testing-flume with a combination of curved sections is set on the tilting-platform. This platform 10 by 100 feet in size is divided into ten sections mounted on pipe-bents which can be lowered

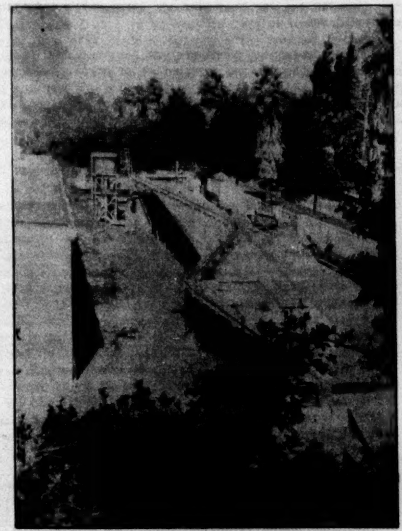


FIG. 2

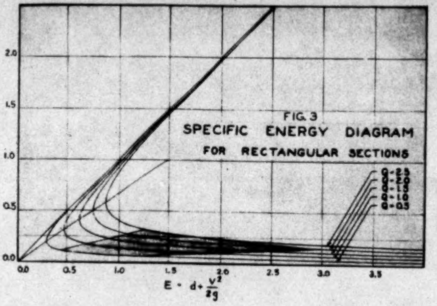


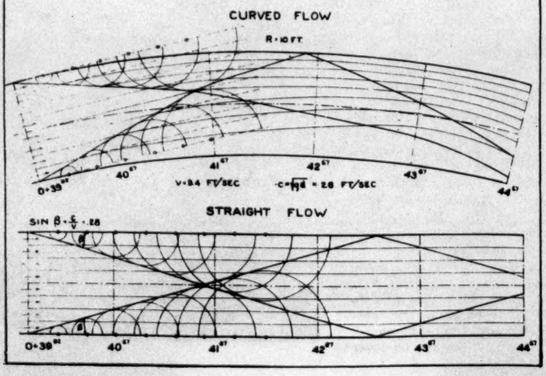
FIG. 3
SPECIFIC ENERGY DIAGRAM
FOR RECTANGULAR SECTIONS

or raised individually. They permit thus the adjustment of the platform over its entire length of 100 feet to any slope between zero and 1 : 10; or, by dividing it into sections of different slopes, any longitudinal profile may be obtained with a total drop at the end of ten feet. For instance, a 1 : 5 gradient may be obtained for half the length of the platform. This makes this structure especially suited to high-velocity open-channel research.

The test-flume consisted of sheet-iron bent to a U-section one foot wide and ten inches deep. Straight sections of 10-foot and 20-foot lengths and curved sections of lengths seven to 15 feet were connected by means of flanges to give the desired configuration. Usually 40 feet of straight flume formed the approach to the test-curve; below the curved section followed a straightaway of 20 feet; after this the water entered another curve and straightaway which carried it to the end of the platform and there to the collection-basin and return-line. Only the upper curve was used for systematic taking of data. The flow in the lower curve was affected by the disturbances created below the first curve and therefore observations there were confined to special cases.

The experimental procedure was comparatively simple in principle. The flume-sections were assembled to the desired combination of straight and curved sections, after the platform had been roughly adjusted to the desired slope. Then the axis of the flume was adjusted more accurately with a transit to a uniform gradient, and cross-slopes were eliminated. Special attention was given to making the section-joints smooth. A certain discharge of water was then established

FIG. 4
PATHS OF WAVE FRONTS



with the aid of the constant-head tank and the Venturi-meter. The velocity at which the water entered the flume was adjusted by means of the movable tongue of the rectangular nozzle to such a magnitude that the depth remained constant over the 40-foot approach-channel. This meant that uniform flow had been established. The testing procedure proper consisted in taking depth-readings at numerous stations and points by means of movable point-gages. In this manner the water-surface configuration in the curved section and the following straightaway was determined and could be reproduced as a contour-map. In addition, cross-profiles of velocity-distribution were measured at selected stations by means of pitot-tubes. The average velocity for any station is given by the known discharge and the cross-section area.

After a run had been completed, a different discharge was established and procedure repeated. In the average four to six runs with discharges varying from 0.5 to 2.5 cubic feet per second were made, after which a new curved section was installed. Nearly all the curves tested had a central angle of 45° and their radii of curvature were 10 feet, 20 feet, and 40 feet. Since the width of the flume was one foot, the relations of width to radius of curvature were 1/10, 1/20, and 1/40, corresponding to prototype conditions. All the curves were tested first for the extreme case of 10 per cent gradient, then the slope was changed to approximately 3.5 per cent for a new set of runs and finally to 1.5 per cent. The range covered by the experiments for each curve is most clearly indicated by the hatched area on the specific-energy diagram shown in Figure 3. The boundaries are formed by the lines of constant discharge on top and bottom, on the left by the velocity-range for one and one-half per cent slope and on the right by that for ten per cent slope.

This diagram is also most instructive in bringing out the fact that the velocities of flow, with which we are concerned in this investigation, are far above the critical. It shows that, below a certain point on any of the curves, the percentage of kinetic energy ($v^2/2g$) in the relation $E = d + (v^2/2g)$ becomes rapidly predominant over the potential energy-content as expressed by d. At this point the total energy-content does not change with a change in the depth d, wherefore we can immediately define it by differentiating the relation for the total energy E with respect to d and equating it to 0. We find that at this critical point the velocity v becomes equal to $\sqrt{gd}$ and we call this the critical velocity. This critical velocity is also the wave-velocity, that is, the velocity with which any infinitesimal pressure-disturbance in water is transmitted to distant points. In still water, for example, a stone dropped into it will cause a circular wave travelling with a radial speed $\sqrt{gd}$. It is easy to imagine now that a rectilinear flow superimposed on this circular wave will distort it, since the part of the wave travelling upstream will proceed with a velocity ($\sqrt{gd} - v$) and the part going downstream with the sum of the two. It also shows that for $v = \sqrt{gd}$ (that is, at the critical velocity) the most the disturbance can do is to send a wave out perpendicular to the direction of flow. If the velocity of flow increases further, the disturbance will be propagated at an angle to the direction of flow, which we may call β, given by the relation $\sin \beta = (c/v) = \sqrt{gd}/v$. If we have now a continuous source of disturbance of the same intensity, waves are sent out continuously, travelling with the same velocity through a flow of constant velocity v. Therefore we obtain a wave-front progressing from the source of disturbance at a constant angle β until it is interfered with. If a wave hits a wall it is reflected and in our case travels back under the same angle β with the opposite wall as indicated in Figure 4. If we assume now a rectilinear flow in a straight channel and two symmetrical sources of disturbance as shown in the Figure, the wave-fronts going out from the two points will not interfere with each other, but cross each other and form a diamond-shaped pattern as has been observed and photographed many times. You may note that the symmetry is maintained due to an assumed constant depth and constant rectilinear velocity, thus keeping the wave-fronts at a constant angle β to the walls. With these facts in mind we can now proceed to the analysis of the phenomenon in curves or bends. In changing the direction of a flowing stream we have to accomplish a change of momentum of the flowing water. This can be done only by applying a certain force which must be proportional to a function of the central angle of turn, that is, $f(\theta)$. This force is built up along the outside bank of a stream, since the velocity-vector there has a component toward the bank and causes a rising water-level. At the inside bank we have the same thing happen only with a negative sign, since the water has a tendency to flow away from the bank. The beginning of a curve must therefore necessarily be the source of a pressure-disturbance. Returning now to our former statement, that pressure-changes in one section of an open stream can only be transmitted to neighboring sections with a velocity equal to the wave-velocity, we can immediately draw the following conclusions:

(1) If the velocity of flow is below and, as in many actual cases far below, the wave or critical velocity, any pressure-change or pressure-gradient is almost immediately communicated to all the stream-tubes of the cross-section and brings about a change in the direction of flow of the entire stream in the same section. All the stream-tubes keep approximately a direction of flow parallel to the bank, or a tangential direction in a continuous curve. The pressure-

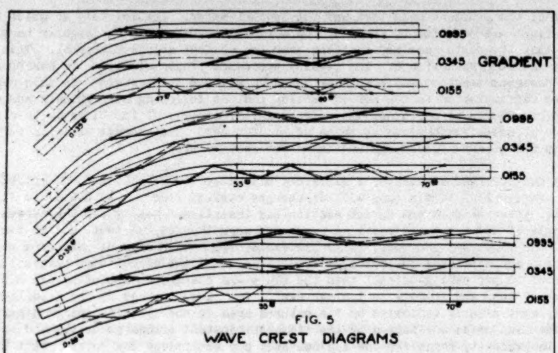


FIG. 5
WAVE CREST DIAGRAMS

CURVES OF 10 FT. RADIUS, 45°
20 FT. " 45°
40 FT. " 22.5°

gradient across any section is in balance with the radial acceleration force per unit-area of circumferential surface, that is, the centrifugal pressure. This assumption gives a convenient solution for the maximum difference of water-surface elevations between the inner and outer banks. The so-called superelevation h becomes $h = v^2b/Rg$, wherein b represents the width of the channel and R the radius of curvature. This formula perhaps with some refinements gives the true value for such a case.

(2) In the case of velocities higher than the critical we have, according to the foregoing discussion, to conclude the following: The pressure-change at the beginning of the inner and outer walls cannot be communicated to the entire stream at once. It reaches neighboring stream-tubes only at points downstream, lying along the wave-front which forms an angle β with the direction of flow. Any particle in the center of the stream, therefore, has no reason to change its direction of flow until it passes under a wave-front, where it becomes subject to an acceleration normal to this wave-front. In Figure 4 we see, therefore, that particles moving in the angle between the two wave-fronts are undisturbed and move in their former directions. As soon as all the particles have passed under the lower depression-wave or the upper compression-wave, the paths of the wave-fronts are subject to the local changes in direction of flow and local changes in depth. This means that, in order to follow the paths any further, we must proceed step by step and determine for each point the local value of $\sqrt{gd}/v$ with regard to the local direction of flow. In this way we get the distorted picture of the diamond seen in the lower part of the diagram. The depression-wave moves toward the outer wall and is speeded up with the increasing depth. The compression-wave moving toward the lower depths near the inside wall is slowing down and may disappear altogether as the depths there go to negligible values.

We may further conclude that the depths near the outer wall will continue to rise until the wave crossing over from the inner wall hits the outer wall and is reflected.

This first return, however, is not the last; the disturbance continues downstream and into the following straight flume-section as shown in Figure 5. This Figure shows a number of observed wave-crests from our experimental runs for three different curves of varying radii of curvature, set to three different slopes as indicated on the diagram. Attention is called to the following striking fact. Looking at the various curves set to the same slope, that is, having the same velocities of flow for corresponding rates of discharge, we find that regardless of the radius the wave-lengths of the disturbances are more or less constant for all the runs and curves. The reason is, that especially in the straight sections downstream, the direction of flow is approximately the direction of the walls again and the wave-fronts depart from and approach the walls under the angle β, which is a constant for a constant relation $c/v = \sqrt{gd}/v$. With lower velocities the angle becomes steeper.

A few words may be said now about the intensity of the disturbance caused by a change in the direction of supercritical flow. According to the experiments we have to multiply the superelevation as determined from (v^2b/Rg) by a factor of 1.6 to 2.2. We may take (v^2b/Rg) as a scale, though it has no meaning in the supercritical velocity-ranges. We may also remember from our specific energy-diagram that the depth-change per unit of total energy-change is larger near the critical velocity than for higher velocities. This may tend to increase the disturbances near the critical depth.

However, the main source of the increase in depth near the outside wall is the fact that the momentum of the flow approaching the wall under an angle θ has to be changed. Therefore the depth-increase must be proportional to $f(v,\theta)$. The magnitude of the disturbances in the downstream straightaway can be expected to vary somewhat with the angle under which the waves hit the channel-walls. Nothing definite may be said, however, at this place, since the investigation has not yet been concluded and since the space allotted for this paper does not permit it. However, the authors anticipate that in the near future it will be possible to publish a treatment of high-velocity flow, based on the above physical concepts, with which it will be possible to calculate both the magnitudes and location of the disturbances caused by changes in direction of flow.

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UNDERFLOW AT WHITTIER NARROWS, SAN GABRIEL RIVER VALLEY, LOS ANGELES COUNTY, CALIFORNIA

James C. Kimble

About a year ago, while in the employ of the California State Division of Water-Resources under the supervision of Harold Conkling, Deputy State Engineer, and George B. Gleason, Senior Hydraulic Engineer, the writer was interested in the problem of underground movement of water from and to the various basins within the South Coastal Basin of southern California. As a method of approach to this problem it was first thought that a reasonable determination of underflow might be obtained by securing an average transmission-constant for the water-bearing material for various areas under consideration, by means of a study of capacities of water-wells and their accompanying drawdowns in offsetting inactive wells--a method previously considered by others. After obtaining the transmission-constant by this method it was planned to determine the total underflow with the use of the slope of the water-table, and the cross-section of the water-bearing material, both of which were known with reasonable accuracy for a number of areas. In a short time it became evident that, while capacities of a large number of wells were available, figures on simultaneous drawdowns in offsetting idle wells were rare. Also other factors, such as pressure-conditions in the aquifers, further complicated the problem.

While working on this problem a method evolved for determining the underground movement of water in an area such as the Whittier Narrows, where there is rising water, without the use of a transmission-constant or cross-sectional area of water-bearing material. It is upon this method, and its application at the Whittier Narrows, that this paper is presented.

The Whittier Narrows is located about ten miles east of the City of Los Angeles. It forms a bottle-necked alluvial-filled gap, connecting the Upper San Gabriel River Valley with the Coastal Plain, and through which passes practically all of the surplus surface and underground drainage of the San Gabriel River and its tributaries--except the Arroyo Seco.

The San Gabriel Valley forms a broad triangle which converges toward the Whittier Narrows. It covers approximately 295 square miles, and has an average width of 15 miles. It is filled with porous water-bearing alluvial debris, derived principally from the San Gabriel Mountains, to a depth exceeding 2000 feet in its central portion. At the Whittier Narrows the San Gabriel Valley is approximately one mile wide. Here the Valley fill has a maximum depth of approximately 1000 feet. A cross-section taken through the water-bearing material at the Narrows would present a surface of about 100 acres (see Fig. 1), while a similar cross-section through the central part of the San Gabriel Valley would present a surface of several thousand acres.

Ground-water, having its primary source as runoff from the San Gabriel Mountains and rainfall upon the San Gabriel Valley floor, converges and flows from all parts of the broad valley toward the Whittier Narrows through which the surplus passes. At the Narrows the quantity of pervious material is inadequate to accommodate the underground passage of the entire surplus. As a result a considerable portion of the water rises to the surface in stream-bottoms above

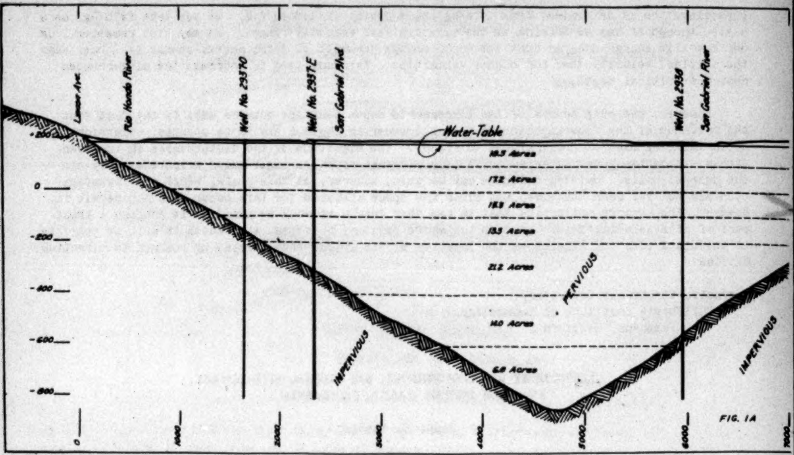


FIG. 1A

the Narrows, and flows through to the Coastal Plain.

Weekly to monthly gages of this surface-flow have been taken since 1923--in the early period by the California State Division of Water-Resources, and in the latter period by the Los Angeles County Flood-Control District. Volume-estimates of the underflow through the Whittier Narrows have long been subject to conjecture. In 1902 Professor Charles S. Slichter made several accurate measurements of the velocity of the ground-water at the Whittier Narrows by measuring with electrical equipment the time required for water charged with dissolved salts to pass between closely spaced shallow wells. Velocities averaging approximately five feet per day were obtained for the coarse pervious material. It is with the use of these velocities that practically all later volume-estimates of underflow at this point have been made.

At the time Professor Slichter's work was done little was known regarding depth and character of valley-fill at the Narrows. For this reason he was unable to make a satisfactory estimate on the total underflow. A number of deep wells have been drilled in the area since that time, and have added considerable information. With the use of this later knowledge, plus Professor Slichter's velocities, a number of estimates on total underflow have been made by various people and agencies, giving values which generally range between 15,000 and 35,000 acre-feet per year--values equivalent to a continuous underflow, ranging from 21 to 47 second-feet. Estimates made by the writer indicate an underflow of 32 second-feet, a value contended to be within a relatively few second-feet of actual underflow.

Assumptions upon which this estimate is based, and which will later be explained are as follows: (1) That the underflow at the Whittier Narrows has been practically constant throughout the 10-year period studied; (2) that the rate of movement of the ground-water in the San Gabriel Valley above the area of rising water is in direct proportion to the slope of the water-table; (3) that in the area immediately above and contiguous to the Whittier Narrows the balance between draft and recharge upon the ground-water is negligible during the comparative periods studied--the figures being taken in December.

The estimate was made by means of a direct calculation with the use of the above assumptions and known changes in rising water at the Whittier Narrows over a 10-year period (see Fig. 2), together with the known change in slope of the water-table in the San Gabriel Valley during the same period. The essential difference between this method and those used previously is that it does not require knowledge of the velocity of underflow, the character and porosity or cross-section of water-bearing material.

At the Narrows the water-bearing material is composed of alluvial sands, gravels, and clays,

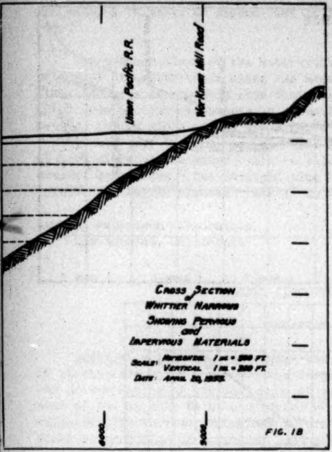

Union Pacific R.R.
Workman Mill Road
Cross Section of Whittier Narrows Showing Pervious and Impervious Materials
Scale: Horizontal 1 in = 500 ft
Vertical 1 in = 200 ft
Date: April 20, 1933
8000
9000

FIG. 1B

with the coarser material predominating. There are no broad clay-blankets between which the ground-water is confined. As a result the ground-water can move vertically with about the same freedom that it moves laterally. For this reason, as long as there is rising water, the pressure-head immediately above the Narrows will be nearly equivalent to the surface-slope in the area of rising water, and naturally will remain practically constant, a condition that would produce constant underflow at the Narrows as long as the slope of the water-table away from the Narrows into the Coastal Plain remained the same. Immediately below the Narrows the surface-flow from the rising water percolates into the stream-beds and tends to hold the water-table close to the surface for some distance below the Narrows (see Fig. 3), thereby maintaining a constant slope.

In recent years the draft in the Coastal Area has lowered the water-table considerably, and no doubt has caused an increase in underflow at the Narrows. However, for the greater part of the period studied it is believed that the slope of the water-table away from the Narrows has not varied more than 15 or 20 per cent. Some loss in pressure at the Narrows, as well as other factors mentioned later, should compensate for the above tendency toward increase in underflow.

The second assumption, that ground-water moves in direct proportion to its head, has been proven with reasonable accuracy by both experiments in the laboratory and water-well production-studies, but under conditions somewhat at variance with those in the field. A directly proportionate relation between rising water and slope of the water-table in the San Gabriel Valley (see Fig. 4) confirms this assumption under field-conditions.

The third assumption, that draft and recharge nearly balance during December in the Whittier Narrows Area, is based upon the following conditions: During the month of December there is generally very little demand upon the ground-water supply--irrigation-requirements are close to a minimum, exports are negligible, and the average daily temperature is low so that evaporation- and transpiration-requirements probably do not greatly exceed the average rainfall for the month plus return irrigation waters. Any balance probably would favor draft. An excess in draft over recharge would tend to give a low value for underflow and vice versa.

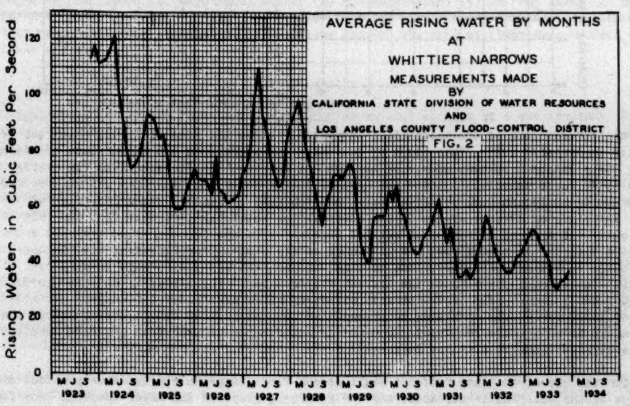
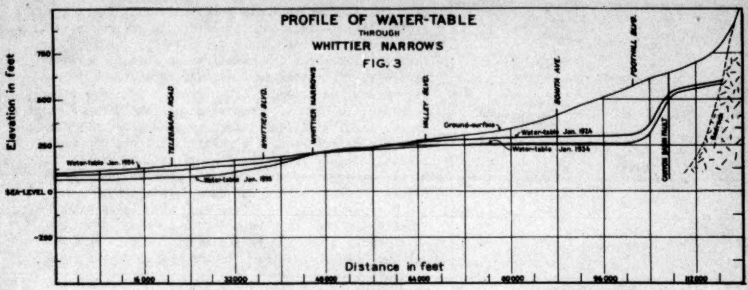
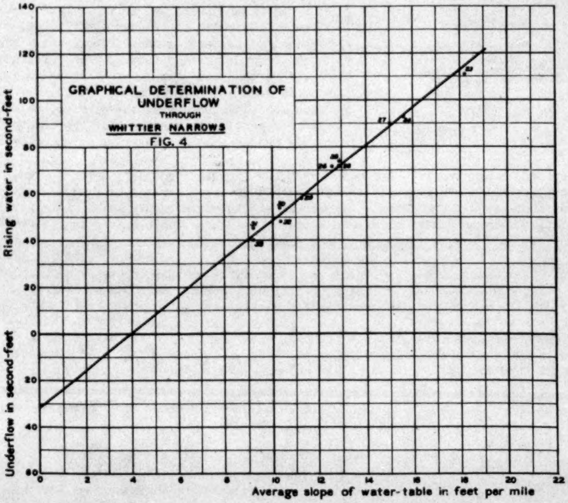


FIG. 2



PROFILE OF WATER-TABLE THROUGH WHITTIER NARROWS

FIG. 3



GRAPHICAL DETERMINATION OF UNDERFLOW THROUGH WHITTIER NARROWS

FIG. 4

The average slope of the water-table immediately above the area of rising water was 18 feet per mile in December 1923. This slope of the water-table produced 112 second-feet of rising water, and a constant unknown underflow through the Narrows. In December 1933 the average slope of the water-table immediately above the area of rising water was nine feet per mile--a slope that produced 40 second-feet of rising water and the same constant unknown underflow at the Narrows. Therefore an average change in the slope of the water-table of nine feet per mile immediately above the area of rising water between December 1923 and December 1933 produced a change in rising water of 72 second-feet and no change in the constant underflow at the Narrows. This is a change in rising water equivalent to eight second-feet per foot change in slope per mile of the water-table immediately above the area of rising water. Therefore, if the average slope of the water-table immediately above the area of rising water were lowered five feet per mile in December 1933, the volume of rising water would be reduced from 40 second-feet to zero, and there would be an average remaining slope of the water-table of four feet per mile responsible for the constant underflow at the Narrows.

With the use of the same ratio of eight second-feet change in rising water per foot change in slope of the water-table per mile, and the remaining slope of the water-table of four feet per mile, a value of 32 second-feet is indicated for total underflow through the Whittier Narrows.

The average slope of the water-table was obtained by taking the difference in average elevation of the water-table along two arcs bordering the area. Average elevation of the water along the arcs was secured from contours of the water-table for December 1923, and annually thereafter from contours on change in elevation of the water-table. Figure 4 shows graphically the average annual slope of the water-table for December in the above-mentioned area, and the average rising water for the same period. The graph indicates negative rising water of 32 second-feet at zero-slope of the water-table--a value representing total underflow at the Narrows under present conditions. The straight-line relationship between rising water and the slope of the water-table may be observed readily on the graph.

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A "CLOSED-CIRCUIT" FLUME FOR SUSPENDED-LOAD STUDIES

Robert M. Oaks and Robert T. Knapp

Scope of suspended-load study--One phase of the study of fundamental problems of dynamics of stream-flow which confronts the Cooperative Laboratory of the Soil Conservation Service is the determination of the influence of suspended load upon flow-characteristics of a stream. Some of the aspects to be considered are: (a) The effect of suspended load on mean velocity, velocity-distribution, entrainment-force, competence, and capacity; and (b) variations of vertical distribution of suspended load with variations of change, variations of grain, and variations of material.

Flume for suspended-load studies--After a thorough investigation of various types of flumes, it was decided to use a "closed-circuit" flume. The basic principle of this flume is the use of a pre-made mixture (water plus solid material) of known concentration which may then be used as a homogeneous mixture.

By means of a "closed-circuit" flume employing this principle, the material-handling problem is simplified, a uniform concentration of solid material is obtained, velocity and depth can be varied independently of concentration and the problem of adsorbed air is eliminated.

Design objectives--Preparatory to the design of a flume of this type, consideration must be given to the individual factors that will produce the desired results. In brief, the following requirements must be fulfilled: (1) Uniform concentration of material in a horizontal plane upon entrance to the flume; (2) adjustable slope; (3) variable depth; (4) uniform flow; (5) uniform entrance-conditions; (6) circulation of water together with suspended load; (7) walls of flume must have negligible coefficient of friction; and (8) rigidity of flume must be such that deflections are small.

Flume-design

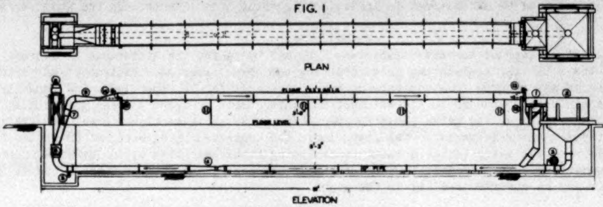
General--Essentially the flume and appurtenant works will consist of a storage-tank, Venturi meter, circulating pump, diffuser, flume, tail-gate, and collection-tank. A schematic drawing of the layout is shown on Figure 1.

Water and solid material will be first mixed in the storage-tank to a desired concentration. The resultant homogeneous mixture will then be pumped to the flume through a depth-control device and discharged through a tail-gate into the collection-tank.

Storage-tank--As previously mentioned, the "closed-circuit" system is dependent on the circulation of a homogeneous mixture in order to gain consentration-control. To this end a tank of 1200-gallon capacity is proposed. A sufficient quantity of water and solid material, necessary to satisfy test-conditions, are to be thoroughly mixed to any desired concentration in this tank before being admitted to the "closed-circuit" system. It can reasonably be expected that a homogeneous mixture will be obtained at this point, but as an additional precautionary measure, the fluid is to be circulated through the system a few times.

Application of this method should insure uniform concentration of material in a horizontal plane upon entrance to flume due to an accurately pre-made mixture and the elimination of ad-

FIG. 1

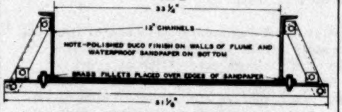

PLAN
FLUME LEVEL
FLOOR LEVEL
ELEVATION

SUSPENDED LOAD FLUME

LEGEND

① COLLECTION TANK 220 GAL. CAP.
② STORAGE TANK 1200 GAL. CAP.
③ VALVE
④ VENTURI METER
⑤ DRAIN
⑥ CIRCULATING PUMP
⑦ FLEXIBLE JOINT
⑧ VARI-DRIVE UNIT
⑨ TRANSITION SECTION
⑩ FIXED PIVOT SUPPORT
⑪ SCREW JACKS
⑫ ADJUSTABLE END SUPPORT
⑬ TAIL GATE
⑭ DIFFUSER

FIG. 2

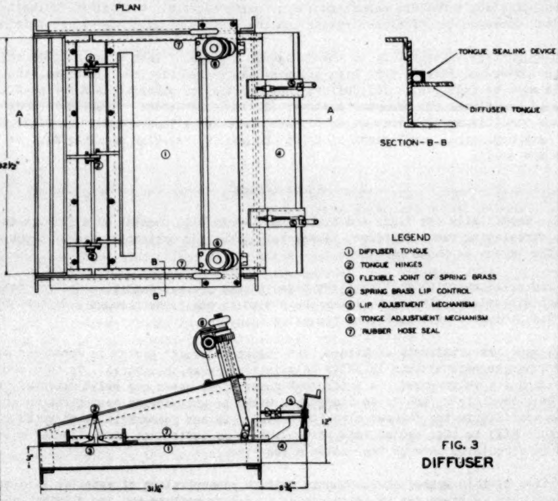

33 ¼"
12" CHANNELS
NOTE-POLISHED DUCO FINISH ON WALLS OF FLUME AND WATERPROOF SANDPAPER ON BOTTOM
BRASS FILLETS PLACED OVER EDGES OF SANDPAPER
51 ⅛"

TYPICAL FLUME SECTION

sorbed air. In addition, variable depth and velocity may be obtained independent of concentration, and a large material-handling problem will be eliminated. The advantages of this method over the customary practice of charging a stream with material by dumping from wheelbarrows or bunkers can readily be seen.

Circulating-system--The circulating-pump and control must handle solid material suspended in water. Consequently, it must be designed so that there is a minimum amount of wear on the apparatus, a minimum amount of grinding of solid material in the water, and satisfactory control of quantity of flow.

In order to realize the above requirements, it is necessary to have (1) high pump-


PLAN
A
A
B
B
32½"
TONGUE SEALING DEVICE
DIFFUSER TONGUE
SECTION-B-B
12"
3"
SECTION-A-A

LEGEND

① DIFFUSER TONGUE
② TONGUE HINGES
③ FLEXIBLE JOINT OF SPRING BRASS
④ SPRING BRASS LIP CONTROL
⑤ LIP ADJUSTMENT MECHANISM
⑥ TONGE ADJUSTMENT MECHANISM
⑦ RUBBER HOSE SEAL

FIG. 3
DIFFUSER

efficiency, (2) low speeds, and (3) variable speed. High pump-efficiency is necessary in order to keep wear on the pump a minimum because loss of efficiency is a measure of the energy dissipated in the pump and resultant wear on parts. Also to keep wear of suspended particles a minimum, the relative velocities in the pump-chamber must be low and this requires low pump-speeds. The use of a throttle-valve to vary the quantity of flow would cause increased turbulence and particle-wear due to excess energy imparted to the fluid during the process. As this is undesirable, variable quantity of flow is to be accomplished by varying the speed of the pump through the use of a variable-drive unit.

The single-stage vertical deep-well pump proposed for use is rated to deliver five cubic feet per second at 7-foot head at a speed of 638 revolutions per minute. Rubber bearings are called for, and the usual stuffing-box where the drive enters the pump-chamber has been eliminated. A stuffing-box is not necessary as the enclosing tube of the pump-shaft will project above the level corresponding to the bottom of the flume, that is, static overflow-level.

Adjustable flume-slope--Velocity-control independent of depth of water is to be made possible through the use of a tilting-flume that may be adjusted to a maximum slope of 1:60. The entrance end of the flume will be mounted on a fixed bearing support and supported in a downstream direction by four pairs of screw-jacks. Another support is provided at the discharge-end for clamping in a fixed position to prevent lateral vibration. Movement in the section between the upstream-end of the flume and the pump will be taken by a flexible joint of rubber hose which can be loosened and clamped into place for each major adjustment of flume-slope.

Uniform flume-slope--As considerable work will be with small slopes, it is important that deflections of the flume proper be small. Deflections not appreciable on large slopes increase to make an appreciable percentage of error on small slopes. Therefore, the flume is designed so that variations of the slope from a straight line will be small and design-calculations give a deviation from true grade of slightly less than one one-thousandth of a foot.

Flume proper--To simulate a stream of infinite width and reduce secondary circulations, the flume-walls must have a negligible coefficient of friction. It is believed that the requirements will be satisfied by the use of a smooth-rubber lining.

The bottom of the flume must be roughened to known degrees for various experimentations. Water-proof sandpaper of a desired grain-size is to be cemented to the bottom and the edges are held down by brass fillets (see Fig. 2). It is particularly adaptable here because the sand-grains are of a fairly uniform size. If at any time in the future a graded base is found necessary, it can be quite simply made.

It is important to insure against any deposition of material in the system in order to maintain concentration-control as it is anticipated working with suspended loads close to the saturation-point. To accomplish this, the cross-sectional area of the flume is designed to be slightly greater than the remainder of the system which will result in lower flume-velocities and hence deposition will occur in the flume first. Since it is contemplated that all work in this flume will be carried on at velocities greater than those permitting deposition, there should be no difficulty with the rest of the system.

Variable depth--Variable depth of water independent of velocity will be obtained through the use of a diffuser (see Fig. 3). Also the use of a diffusing section will give a greater effective length of flume as it will reduce the distance necessary to obtain equilibrium-conditions.

Water is to enter the diffuser through a rectangular opening, 3 inches by 33-1/4 inches, and there be diffused or spread to depths between three inches and nine inches by means of an adjustable tongue which hinges near the entrance to the diffuser. Although this design is not conventional, a similar arrangement has been used with success in the California Institute of Technology Laboratory. A 3-inch minimum and a 9-inch maximum depth of water will cover the normal range of experimentations. The joint between the body of the diffuser and the tongue is to be made of spring brass in order to make it water-tight and yet flexible. Special hinges are specified in this conjunction to carry the shear-load. A screw-control mechanism is provided for tongue-adjustments. A spring-brass strip extends beyond the end of the tongue. By adjustment of this lip through the control-mechanism shown, fluid discharging from the diffuser can be deflected parallel to the slope of the flume. Due to the movement of the tongue along the walls of the diffuser, a seal must be provided to prevent leakage. An angle is to be welded along the edges of the tongue encasing a rubber tube which will be inflated to a pressure sufficient to prevent leakage.

Uniform-flow--In order to maintain uniform flow and uniform depth which govern the major portion of tests as now envisaged, a tail-gate in the form of an undershot-weir is to be installed at the discharge-end of the flume. Also the use of a tail-gate will eliminate the "drop-down" curve at discharge and thus make possible a longer working section of flume. The undershot-weir of parabolic profile has been used for some time in the Institute Laboratory with satisfactory results.

Circulating-system--The "closed-circuit" system is to be constructed in a vertical plane to eliminate pipe-bends and reduce wear to a minimum. Also wear may be kept a minimum by pumping against a low head, which condition will be established by keeping the collection-tank full. When water and suspended load is pumped from the storage-tank, the water-level in the collection-tank will follow that in the storage-tank. As the draw-down is several feet, an additional volume of mixture will be necessary to fill the collection-tank. In order to supply this additional volume, the tail-gate at the discharge-end of the flume is to be closed and thus an additional volume of water over and above that needed for the run may be stored in the flume. Upon closing the discharge-valve from the storage-tank, the tail-gate can be raised and circulation started. An adjustable overflow-weir is to be installed between the collection- and storage-tanks to take care of surplus volume in the circulating-system.

Conclusion

The fundamental aspects of suspended load as it affects the dynamics of stream-flow is of great importance not only to hydraulic research but also to the Soil Conservation Service in its study of the erosional problems confronting the country today. Research of this nature has been somewhat limited in the past and it is believed that results obtained from studies carried out in a flume of the above construction will add materially to the knowledge concerning the phenomena of suspended load.

Cooperative Laboratory of Soil Conservation Service, United States Department of Agriculture,
and California Institute of Technology,
Pasadena, California

EXPERIMENTS WITH CRITICAL-DEPTH FLUMES FOR MEASUREMENT OF FLOW IN DEBRIS-LADEN STREAMS

H. G. Wilm, J. S. Cotton, and H. C. Storey, Jr.

HYDROLOGIC ASPECTS OF THE SAN DIMAS EXPERIMENTAL FOREST

C. J. Kraebel and J. D. Sinclair

SOME CONSIDERATIONS ON THE BEHAVIOR OF ROCK-DEBRIS AND SILT-PARTICLES IN STREAMS AND RESERVOIRS

George H. Otten and Vito A. Vanoni

No manuscripts or abstracts were submitted for these three papers.

AMERICAN GEOPHYSICAL UNION

Pacific Coast Meeting

WESTERN INTERSTATE SNOW-SURVEY CONFERENCE

JOINT MEETING WITH

SECTION OF HYDROLOGY

Pasadena, California
January 31, 1936

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STATUS OF COORDINATION AND STANDARDIZATION OF SNOW-SURVEYING

James C. Marr

Snow-surveying for stream-flow forecasting has now grown to interstate, national, and even international importance. It was conceived and developed to fit conditions and needs of our western states by Dr. J. E. Church in the Lake Tahoe Region of Nevada. From this point it sent roots elsewhere and broadened to its present scope, largely through the initiative of individuals working independently and under various exigencies.

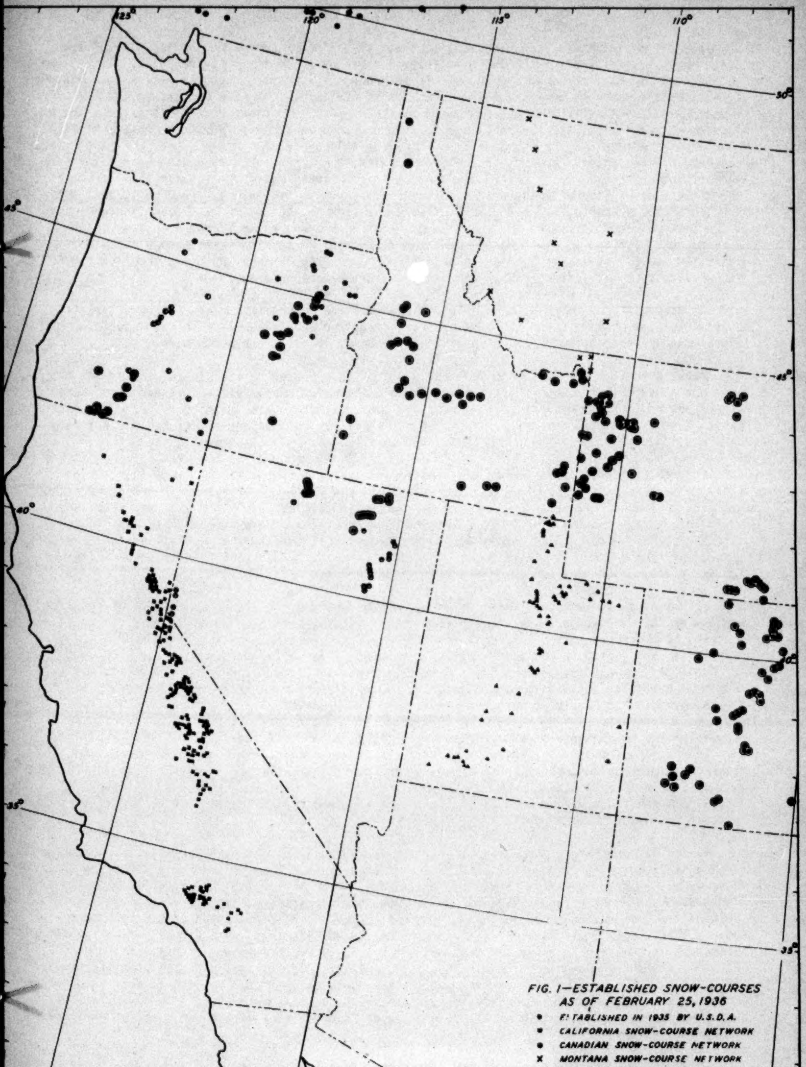
This manner of expansion, though resulting in noteworthy progress that probably otherwise would not have occurred, has had an inherent fault. There has been a constant tendency toward independent rather than concerted effort. To make of these present activities a service of full value to the country at large, further coordination of effort and standardization of procedure is required.

Cognizance of this fact has been taken heretofore by leaders in this work, but they have been handicapped in the endeavor. Through conferences and published reports they have generously pooled information, experience, and ideas for consideration and guidance of all who are, or should be, actively engaged in snow-surveying. This has been a step in the right direction and by all means it should be continued, but a helping and guiding hand with the means for keeping in touch with, and for lending support to, all such work has been needed to complete the transition. Now that one is being trained for the purpose it appears that we may look forward with greater confidence and enthusiasm to the future of this public service.

The proffered helping hand is no less than that of the Federal Government represented by the Bureau of Agricultural Engineering of the Department of Agriculture. It has been busy in this capacity for a little more than six months, which is hardly sufficient time to justify a demand for an accounting. Were it not for the progress made prior to that time by the other agencies and the generous spirit of cooperation met with on all sides, little indeed could be reported as accomplished. As it is, a recounting of preparations and plans for major operations ahead is perhaps of greatest interest.

The first act of the Bureau was to canvass the situation to ascertain the opportunities for correlating the then existing snow-surveys and need for starting the work where it had not existed before. Two parties were sent into the field. Dr. J. E. Church and Professor G. D. Clyde were drafted for the purpose. I accompanied Professor Clyde on this occasion and, as a result, can give first handed the findings in eight states and a portion of Canada. Generally speaking, a very favorable attitude was found to exist. Without exception directors of established snow-survey work expressed a desire to become a part of the cooperative system of the Government. Elsewhere there was found sufficient appreciation of the possibilities of the work to give assurance that it would be well received if started and supported to some extent in one way or another. Usually local funds that might be used for the purpose were either inadequate or non-existent. Offers amounting to substantial, material aid were obtained for the asking from several other Federal bureaus and services. The response was general, though more spontaneous in regions where water-resources are fully developed and used. It can be said without reservation that a receptive attitude towards a unified, standardized water-supply forecasting-service exists throughout the area covered by the canvass.

It was decided for the present to concentrate efforts within seven states, that is, California, Nevada, Utah, Oregon, Wyoming, Colorado, and Idaho. Since fairly complete state-wide snow-survey programs under the auspices of either the State engineer or the State agricultural college are already well under way in the first three-named states, little beyond the need for coordinating these efforts is required. Aside from the operating features of the work in Nevada and Utah, considerable snow-survey research has been conducted. It is intended that this too will become a part of the cooperative program of the Government. A similar state-wide operating program exists in Oregon, though more detailed Federal aid is required there. Except for several isolated pieces of work in Idaho the other three states have been totally without a service such as is planned. The importance of the water-resources of these states to irrigators and industry in them and surrounding states makes of this territory an indispensable key to a complete, unified interstate water-supply forecasting-service. The major contribution of the Bureau of Agricultural Engineering this year towards effecting a country-wide water-supply forecasting-service has been to establish the work in these regions. In endeavoring so to do, considerable experience has been gained. In accordance with the precedence that has been set, a full account of this experience is offered in the interest of maintaining unity in the work.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● ESTABLISHED IN 1935 BY U.S.D.A.
▪ CALIFORNIA SNOW-COURSE NETWORK
● CANADIAN SNOW-COURSE NETWORK
× MONTANA SNOW-COURSE NETWORK
⊙ NEVADA SNOW-COURSE NETWORK
● OREGON SNOW-COURSE NETWORK
▲ UTAH SNOW-COURSE NETWORK

FIG. 1—ESTABLISHED SNOW-COURSES AS OF FEBRUARY 25, 1936

A snow-sampler having the essential features of the Mount Rose type and closely modeled after the one developed in Utah has been furnished this year to start the new work. It will be put through rigorous tests before the season is ended and upon their outcome will depend whether it will be necessary to make changes or not. It is similar to the Utah sampler in type of weighing-scale, diameter of cutter, and material of which it is constructed. It differs therefrom in cutter-design, and the tube is made up of 30-inch sections in somewhat heavier alco-aluminum stock than that of the Utah tube. The outfit comprises a cutter, tube, weighing-scale, and cradle. Accessories are not included. Considerations governing its choice were light weight, convenience in handling, interchangeability of parts, and last--but far from least--cost. The first tube-section with cutter, scale, and cradle weighs two pounds. Each additional tube-section weighs approximately one pound. Thus a sampling set including 7-1/2 feet of tube would weigh four pounds. All parts are interchangeable from one set to another. According to observers, who must travel for long distances on skiis, the 30-inch tube-sections will be more convenient to pack than the longer sections now in use. The purchase price varied from $32.55 for a 7-1/2-foot tube-set to $65.29 for one with 17-1/2-foot tube-set.

A metal notebook-cover with snow-course sketch attached and filler consisting of printed instructions to observers and white, waterproof forms for snow-cover measurements identical with those used by Professor Clyde in Utah are also being supplied for this new work.

Metal porcelain-enamel snow-course markers will be provided by the Federal Government where they are acceptable to cooperators. The snow-course markers embody visibility and identification of purpose and imply a Federal-State activity. The trail-signs are intended to serve merely to guide observers to snow-courses. It will be recognized by all concerned that the activity should have a standard in this respect and it is desirable that accord be reached in the matter.

Several parties, working under the same instructions, laid out the new snow-courses and made the necessary arrangements for measurements of snow-cover. Professor G. D. Clyde assisted by Ralph L. Parshall established the 43 snow-courses in Colorado and 28 in Wyoming, which are shown in Figure 1. The 77 for Snake River Drainage and a few others were established, or reestablished, by myself. R. A. Work, Bureau of Agricultural Engineering, established or reestablished the ten in Rogue River Drainage. Consultations were held before this field-work began. Agreement to be guided by the following suggestions was reached:

(1) At least the minimum number of snow-courses necessary to represent effects of prevailing storms be established in each important drainage-basin.

(2) Snow-courses be located above the zone of winter-melting.

(3) Erratic drifting and wind-swept conditions be avoided.

(4) That snow-courses consist of two or more lines having different bearings, with total length as nearly one-half mile as is feasible, and that stationing range from 25 feet to 100 feet to provide, as nearly as may be, 25 points of measurement.

(5) All snow-courses be surveyed and sketched at the time of selection of site and observer be present during this operation and receive instructions as to duties.

(6) So far as possible, arrangements be made for measurements of snow-cover through interested organizations having permanent employees who can either make the measurement themselves or will be responsible for them.

(7) At least one measurement of snow-cover be made each year, the time to be immediately prior to the usual melting period in spring.

My own personal experience in this phase of the work may hold further interest. Upon entering a drainage-area my first act was to locate an organization that, conceivably, might be interested in the program. Usually it was the United States Forest Service, though about half was arranged for through other organizations. Snow-surveying for stream-flow forecasting was carefully explained in each instance, followed by a request for voluntary cooperation of a nature that would not be unduly burdensome. The lay of the region was examined, with each of these agencies, for favorable snow-course locations that met accessibility requirements. Without exception fairly satisfactory snow-course networks resulted and arrangements that were made for the measurements of snow-cover are considered permanent. This confidence is held because in each case the cooperating organization has been convinced of the value of measurements of snow-cover to them; each responsible field-agent is a full-time employee; and the work is equitably and considerately apportioned out.

In length and design of snow-course, departures from ideals were found necessary or desirable in some cases. The practice of adhering, when in doubt, to the long, elaborate snow-course has merit, but it appears to me that the observer should not be unnecessarily burdened in this respect merely to uphold an arbitrary standard.

A matter of far-reaching importance is the manner in which the data will be handled and service correlated. Regional offices are planned--perhaps as many as one to each State--and these will be manned sufficiently so that with the assistance of the cooperators, a dependable snow-survey, water-supply forecasting unit will presently begin to function. We will have the cooperation of the Weather Bureau, the Forest Service, the Bureau of Reclamation, the National Park Service, the Geological Survey, the State Engineers, the Agricultural Experiment-Stations, and many local official and corporate agencies.

Much obviously has still to be done to bring about a smoothly-working organization and the continuing interest and help of this Conference will be most welcome.

Bureau of Agricultural Engineering,
United States Department of Agriculture,
Boise, Idaho

PRECIPITATION-SURVEYS FOR ANTICIPATING WATER-SUPPLIES

H. K. Burton and J. Cecil Alter

Salt Lake City depends chiefly for its water-supply on the flow of five mountain-streams, all heading high in the Wasatch Mountains within 25 miles of the heart of the City. These streams are in turn chiefly dependent on the amount of precipitation of rain and snow over the drainage-area lying between elevations of 6000 and 9000 feet.

An outstanding characteristic of the discharge of these streams is the relatively low stages in the late summer and through the winter; and more especially the comparatively excessive flood-discharge in the late spring and early summer months, usually for only a few weeks in May and June; this is when the mountain-snow is melting most rapidly, or is in fact, just leaving the major mountain-basins.

Practically all mountain-streams go into flood when the high-level snows are melting at the most rapid rate; but, in the case of the streams in the northwestern quarter of Utah, another factor of major importance is operative, namely: The season of maximum precipitation usually occurs during March, April, and May generally over the valleys and the greater portion of the watersheds; it occurs as early as January, February, and March at the higher levels of more limited drainage-area. Consequently the charge or supply of ground-water which is always depended on for giving all streams a more steady, dependable flow, has not usually been received until just prior to the melting of the surface-snow stores in right early summer.

Thus what actually occurs in a normal year is that the ground-water supply and its contribution to the streams attains a peak about the same time the surface-runoff occurs from the snow in the mountain-basins. The result is the Salt Lake City streams, for example, go into excessive flood for a brief period in every normal season, not only necessitating much care and attention in impounding and conserving the water while it may be had, but in holding damage and losses by flood to a minimum.

All years of excessive precipitation and many seasons of more nearly normal flow send water down the stream-channels to waste into Great Salt Lake in greater or less quantities, because it comes faster than it can be cared for in the steep stream-beds or than it can be utilized on the fields of the valley. The most strenuous activities in the Salt Lake City Municipal Water Department are concentrated in the few spring or early summer flood weeks, when the water-crop must be garnered or harvested into storage, either by pre-irrigating the field-soils or impounding in reservoirs, in order to supplement the subsequent moderate or relative low stream-discharges until the coming of the next water-season.

Needless to say, the municipal water-authorities, as well as the irrigators and industrial users of water in the Salt Lake Valley--and for that matter, in the adjacent Utah valleys--come to look to the skies for their help, the rains and snows from which are the direct sources and controls of water and of human life and activity.

Consequently, since the year 1915, the Salt Lake City Water Department has cooperated with the United States Weather Bureau in maintaining precipitation-measurement stations at representative points over the five principal watersheds, and in making regular snow-surveys or measurements of the surface-snow depth and water-content accumulated on the ground.

The precipitation in a normal year is at its annual minimum in the months of June, July, August, and September; but the monthly amounts steadily increase to a maximum in late winter and early spring. Since the so-called "normal" year is the one that practically never occurs, precisely, in natural phenomena generally, all local water-authorities have a lively concern in the current and past meteorological history of the Salt Lake Valley, and of the adjacent mountain-area, from about the first of October every year.

In fact, the influence of an abnormally dry, or an abnormally wet, summer season is very often felt in the subsequent "water-season"; for the deep ground-water supply may be notably deficient or abundant, demanding a toll of much or little from the subsequent supply, which, by the way, may be either deficient or excessive without regard to excesses or deficiencies occurring during the previous summer. Thus when a dry summer is followed by a dry winter there is much to be done in advance toward conserving every possible gallon of the available water and toward making plans to get along with little. Previously impounded waters are not wasted, and every practicable conservation- and regulation-practice are enforced before it is too late.

A foreknowledge of these facts, which is gained exclusively from the current precipitation and periodical snow-cover measurements, enables the water-authorities to anticipate the coming conditions to a certain extent, and always to mitigate materially their bad effects.

A refinement has been introduced recently in the snow-survey work, through the establishment of several new snow-courses by Professor George D. Clyde, snow-survey leader, representing the Utah State Experiment-Station and the State Engineer. All courses are to be measured March 31, using Professor Clyde's improved instruments.

The mountain snow-layer melts continually from the bottom, the moisture leaching steadily into the soil; so that usually no more than 50 or 60 per cent of the annual moisture-supply is still available in the surface-snow stores on the last day of March at the Brighton or Silver Lake elevation of 8700 feet.

By maintaining daily precipitation-measurements and semi-monthly surface snow-surveys at Silver Lake, for example, and stream and other measurements elsewhere, the municipal water-authorities are able to apply current, up-to-date debit and credit entries against the water-account, and to determine more or less precisely how much water has gone through the stream-measurement weirs, how much water has been impounded in the reservoirs, how much moisture has been precipitated on the watersheds, how much moisture is still on hand in the form of snow on the ground, and how much moisture has already gone into the soils to come out later.

These data are usually compared with normal, either directly or by percentages; and comparisons are also made with figures for the previous season, which are still fresh in memory. It is also often advantageous to make comparisons with other years when there were certain well-remembered reservoir-stages or water-curtailments, and especially the seasons of greatest or of least water-supply of record.

These figures are always minutely scrutinized and considered in connection with the plans and operations of the Salt Lake City Municipal Water Department. But the comparisons with conditions in well-known years, and more especially the last previous year, are especially valuable in making appeals to the general public, in enlisting cooperation in the conservation and beneficial use of water in seasons of deficiency.

For maintaining this kind of leadership over hundreds of thousands of water-users, whose dole of water is never twice alike and is never as abundant as they could wish, and for keeping informed, currently and in advance, of water-supplies, available and prospective, there seems to be no adequate substitute for the daily precipitation-records and semi-monthly and March 31 surface snow-surveys, such as have now been maintained for twenty years with gratifying results by the Salt Lake City Water Department cooperating with the United States Weather Bureau.

City Water Department and U. S. Weather Bureau,
Salt Lake City, Utah

THE EFFECT OF SOIL-ABSORPTION ON SNOW-SURVEY FORECASTING OF STREAM-FLOW

H. P. Boardman

All who expect from the title of this paper to hear a definite statement in the shape of a mathematical relationship, will meet with disappointment. In my opinion it is not economically feasible to determine quantitatively either the total precipitation or the total absorption-losses for a given basin of any considerable size, and fortunately our method of snow-surveying does not require such quantitative determination.

It is also difficult to see how soil-absorption losses can be separated from evaporation- and transpiration-losses on the large scale of a drainage-basin though of course transpiration and soil-evaporation losses are experimentally determined on a relatively small scale for certain soils and certain kinds of vegetation by laboratory-methods.

Other things being equal it seems reasonable that the usual behavior of absorption and other losses should be as follows: In a year subnormal in winter precipitation the actual quantity subtracted by the soil in spring and early summer may be about the same as such subtraction in a normal year, thus leaving a much smaller proportion of the precipitation to run off on the surface. Likewise in a year of supernormal winter precipitation the soil-subtraction would be about the same as in a normal year thus leaving a larger proportion to run off on the surface. Table 1 illustrates this numerically.

Table 1

Year	Precipitation	Loss	Runoff	
	inch	inch	inch	per cent
Normal	40	16	24	100
50 per cent	20	16	4	17
150 per cent	60	16	44	183
40 per cent	16	16	0	This never happens

Assume a basin with a normal precipitation in winter of 40 inches and normal loss of 16 inches leaving 24 inches for normal runoff. For a 50 per cent winter the precipitation would be 20 inches and, if the losses were 16 inches as in a normal year, that would leave a runoff of 4 inches or 17 per cent of normal runoff for 50 per cent precipitation. For a 150 per cent winter the precipitation would be 60 inches and, if the losses were 16 inches, the runoff should be 44 inches which is 183 per cent of normal runoff for 150 per cent precipitation. One trouble with the above illustration is that in a 40 per cent precipitation-year or less, the losses would be the full amount of the precipitation, resulting in no runoff, and we know that there is always some runoff.

In the discussion following this paper Fred H. Tibbetts took exception to this statement, citing some watershed with which he was familiar, where absolutely no runoff occurs in very low-precipitation years. However in the region for which I help work up the forecasts, we have no record of any year when runoff was entirely lacking. My next paragraph states the limitations of my point of view.

Before I go further I must state that I am thinking in terms of the eastern slope of the Central Sierras where most of the precipitation producing runoff occurs in the form of snow and where we use the April 1 snow-surveys in attempting to forecast the runoff for the following April to July. I am not attempting in this short paper to discuss other types of terrain or climate.

Notice that in discussing the effect of absorption-losses on runoff in subnormal and supernormal years I began with the expression, "other things being equal". That is an easy phrase to use, but in this matter of snow-survey forecasting of runoff, "other things" are seldom if ever equal. Some of the "other things" to bear in mind as affecting the problem are: Spring and summer precipitation during the runoff-period; previous autumn precipitation as rain or early snow which melts before the onset of winter; elevation of ground-water before winter snows set in, which is in some cases dependent not only on fall rains but precipitation for months or perhaps several years previously; temperature at all times from October to the following July. Topography, texture and depth of soil, and character of bedrock affect capacity for holding ground-water and also facility of conducting water from melting snow or spring rains to stream-channels.

I will take some illustrations from the Truckee and Tahoe basins. The Truckee River is the outlet of Lake Tahoe and in turn it empties into Pyramid Lake, Nevada, which is a brackish desert-lake without other outlet than evaporation. In forecasting we treat them separately as the Tahoe Basin and the Truckee exclusive of Tahoe, since the Lake is controlled by outlet gates. There have been several years when neither absorption-losses or any other factors which we have been able to evaluate have explained discrepancies.

I will only consider comparatively recent years, since most of our present snow-courses have been in use (see Table 2).

Table 2

Year	Truckee River		Lake Tahoe		Precipitation previous fall	Spring and summer precipitation Tahoe City	Spring temperature
	Snow-survey	Run-off	Snow-survey	Rise.			
	per cent of normal					per cent of normal	
1921	100	80	88	89	High	80	About normal
1922	131	128	135	125	....	79	April, -9°2; May, normal
1924	40	16	39	15.5 (27 inflow)	Very low	26	April, +1°4; May, +7°6
1931	40	22	34	30	Normal	88	....
1927	104	122	96	124	Very high +8°9 in Nov. at Summit	150	....
1932	105	89	112	102	4 years low precip. 40 o/o to 67 o/o	April to May, 46 April to June, 71	....
1933	73	49	81	50 (65 inflow)	3" to 4" below normal at Summit and Tahoe City	62	May, -7°8 Cold all Calif. and Nevada

In 1921 the runoff of Truckee Basin was about 80 per cent of normal and the snow-survey above 100 per cent. The previous year was low but rains during the fall were high. Rains during April to June were 80 per cent of normal and temperatures during the spring were not much away from normal. Probably a deficiency of snow in low latitudes is the main explanation of the low runoff as no good low-level courses were in use in the Truckee Basin at that time and the low-level courses near Tahoe were only 60 per cent to 70 per cent of normal. The rise of Tahoe checked the snow-survey much closer that year, both being slightly under 90 per cent.

In 1922 the runoff of Truckee Basin was nearly up to snow-survey, 128 per cent and 131 per cent respectively with a very low runoff in April, due to a temperature 9°2 below normal, but high runoff in May and June with temperature nearly up to normal. This year the agreement of snow-survey and runoff is good enough to need little comment.

The year 1924 was very low with 16 per cent runoff from a 40 per cent snow-survey, the previous fall being very low in precipitation and the precipitation during April to June being only 26 per cent of normal. The normal precipitation during April to June at Tahoe City is 4.4 inches. The temperature for April was +1°4 and that for May was +7°6 from normal. There was little left to runoff after May. Ground-absorption must have accounted for a large part of the drop from 40 per cent snow-survey to 16 per cent runoff. The rise of Lake Tahoe was only 15.5 per cent though the estimated inflow into the Lake was 27 per cent of normal; the discrepancy probably may be explained by normal evaporation, accompanied by great deficiency in precipitation during April to June on surface of Lake.

The year 1931 was about the same as 1924 in snow-survey, but rains during the previous fall were normal and rains during April to June were 88 per cent. The runoff was 22 per cent of normal, six per cent of normal better than in 1924.

The year 1927 was the best year since 1922, giving a runoff of 122 per cent and rise of Lake Tahoe of 124 per cent of normal with a snow-survey of about 100 per cent. The precipitation during the previous fall was 12.9 inches for November or 8.9 inches above normal at Summit and nearly as great at Tahoe City. This evidently greatly cut down the absorption during the spring and in addition, the precipitation during April to June was 150 per cent of normal. The temperatures in spring were practically normal.

The snow-survey for 1932 was about 105 per cent for the Truckee Basin and 112 per cent of normal for the Tahoe Basin, while the runoff of the Truckee was only 89 per cent and the rise of Lake was 102 per cent. Previous to 1932 there had been four years in succession of low precipitation, the snow-surveys ranging from 40 per cent to 67 per cent of normal, probably lowering the water-table considerably. It was very noticeable that early melting on the low levels around

Tahoe had little effect on the elevation of the Lake. At Hobart Mills, five miles north of Truckee, the custom was usually to lay down a large amount of planking in the spring to travel on because of mud, but the statement was made by the manager of the sawmill that, in spite of the rather heavy winter snows, there was in 1932 much less mud to contend with than usual. I believe this lack of mud was because the water from early melting penetrated deeply into the soil because of low water-table and did not saturate the soil near the surface. I think this depletion of the water-table caused considerable loss of runoff-water that year. There are considerable areas east and northeast of Truckee which appear to have very deep soil.

In 1933 the snow-survey was 73 per cent of normal for Truckee and 81 per cent for Tahoe but the runoff was only 49 per cent and the rise of the Lake was 50 per cent. The precipitation during the previous fall was deficient three to four inches at Tahoe City and Summit and the precipitation during April to June was 62 per cent of normal, but I attribute a large part of the shortage in runoff to the excessively low temperature in May, which was 7°8 below normal. It was an unusually cold May all over California and Nevada.

May is usually the month of largest runoff for the Truckee, the normal being 120,400 acre-feet, while that for April is 95,700 acre-feet, and that for June is 80,800 acre-feet.

My belief is that a cold May results in an actual loss in the following manner: The lower altitude snow being largely melted in April bares the ground back to the edges of the snow-banks in the higher altitudes, where it probably only thaws slowly for a few hours of the day, freezing every night, so that the small runoff from the snow-banks largely goes into the ground instead of collecting in the larger drainage-channels in sufficient volume to flow down to the streams at lower altitude. This water thus taken into the ground at high altitudes keeps the ground wet but considerable portions of it are evaporated from the surface before reaching the lower altitudes. A warm May on the other hand thaws the snow rapidly so that it collects in the channels and flows down to the larger streams.

One project that would no doubt help us in forecasting is the insertion of pipes in the ground at numerous places and the observation and recording of the fluctuations of ground-water level. We have not yet had the finances to carry out that work on the eastern slopes of the Central Sierras. I also think more observations of precipitation and temperature in the high altitudes would be a great help, since our rains in spring and summer are frequently quite local in character and probably temperature-changes at certain times do not run parallel over extended areas.

Nevada Cooperative Snow-Survey,
University of Nevada,
Reno, Nevada

CALCULATION OF NORMALS FOR USE WITH SNOW-SURVEY DATA

Charles H. Lee

There are two well-recognized methods of forecasting summer runoff from snow-survey data. These have been termed, respectively, the area- and the percentage-methods. The area-method gives quantitative results but requires the gathering of such detailed field-information that it is costly, and with present imperfect knowledge of watershed-losses, is generally too inaccurate for dependable use. The percentage-method, where applicable, gives results which are more reliable and is the one now generally followed in the West.

In the percentage-method the average snow-cover for any period of time is expressed as a per cent of the normal for the same period. The method has its origin in the fact that winter snow on mountain-watersheds is usually derived from general storms whose yield is relatively uniform over areas large enough to embrace one or more stream drainage-basins. By averaging the results from a number of well-selected survey courses within a drainage-basin, it has been found possible to derive a percentage applicable to the whole drainage-basin. The method is not applicable to drainage-basins in which storm-areas are small in comparison with the drainage-area.

One difficulty in applying the percentage-method is the obtaining of stable normals for snow-cover. Several kinds of hydrologic data have been used as a basis for computation, among which in order of dependability may be listed the following: (a) Long records of snow-cover on the basin; (b) long records of natural runoff from the basin or from an immediately adjacent basin with similar characteristics of rainfall and runoff; (c) long records of local precipitation within the basin; (d) long records of precipitation within the region of precipitation which includes the basin; (e) in the absence of any of the above, the first year's results may be used as a standard and following years compared with them until enough years have elapsed to derive a stable normal.

In selecting the method for computing normals, the first question which arises is the length of record required to obtain a stable value. Since precipitation is the principal factor controlling the amount of both snow-cover and runoff, it is a reasonable conclusion that the period of years required to obtain a stable precipitation-average would apply to all of the above-listed methods. Much study has been given to this subject both in the United States and in foreign countries. As a general rule it may be stated that in humid regions an average based upon 25 years of record is reasonably dependable. Semi-arid and arid regions, however, are subject to protracted dry cycles which frequently extend over periods of from five to ten years, and occasionally exceed fifteen years. A 25-year record is too short for intervening wet years to fully counteract the effect of such long dry periods, so that in semi-arid and dry regions a period of 40 to 50 years is necessary to provide a stable normal. A record even of this length may be modified by excessively long and severe periods of deficient precipitation, such as that in Central and Northern California commencing in 1918 and continuing beyond 1930. Such periods, however, occur at long intervals, possibly exceeding 200 years, and should not be given too much weight in determining normals for snow-survey work.

Snow-records--Systematic snow-surveying is of such recent origin that there are as yet no records of snow-cover of sufficient length to serve as an independent basis for computing normals. In a few instances the first two or three years of record, either individually or in combination, were normal with respect to precipitation and runoff, and it was considered that the average of snow-cover during these years represented a normal. It is also possible that horizontal sampling by one-foot layers at monthly intervals in various typical locations might show a relation between depth of snow on the ground, time, and density by which the long snow-depth records of the United States Weather Bureau could be utilized. In general, however, it is at present impracticable to compute normals from snow-cover observations alone, and other types of records must be considered when determining snow-cover normals.

Runoff-records--In certain respects properly selected records of runoff may be superior to long records of snow-cover in determining normals. Runoff is the quantity which is being forecast, and measurements of runoff automatically correct any abnormal loss of snow subsequent to measurement such as evaporation or soil-absorption. The ideal record of runoff is one of 25 to 40 years in length, unaffected by diversion or artificial storage, and not appreciably influenced by late rains in spring and summer. Where direct diversion or storage occurs above a stream-gaging station, correction to natural runoff quantities can often be made from diversion-records. In certain instances it is also possible to separate melting-snow runoff from rain-runoff by detailed study of a daily or hourly hydrograph of stream-flow, and thus make correction for it. If records of runoff are used they should be for the same drainage-area as that for which snow-cover is measured, or for immediately adjacent drainage-areas whose characteristics of precipitation and runoff are similar. In order to determine the degree of similarity, study should be made of the relative conditions of topography, geology, soil, and vegetation, as well as stream-flow peculiarities as shown by a daily hydrograph.

Precipitation-records--Records of precipitation are more numerous and of longer duration than those of runoff, and hence are frequently the best records available for computing snow-cover normals. There is a fundamental difference between the seasonal variation in precipitation and runoff, however, which should be recognized. Runoff is a residual quantity, being the portion of precipitation which escapes watershed-loss by evaporation, transpiration, or absorption, and is fairly constant from year to year. Hence runoff has greater annual fluctuation than precipitation has. In dry years the percentage runoff decrease is greater than for precipitation, and in wet years the percentage increase is greater. Furthermore, the effect of dry years in depleting soil-moisture may extend into a subsequent year. In using a record of precipitation for establishing snow-cover normals, it is safer to make comparison only for years when precipitation has moderate departure from the normal. The most reliable records of precipitation are those from 25 to 40 or more years in length, located within or immediately adjacent to the basin. If precipitation-characteristics differ within the basin, as is frequently the case for those on the lee-slope of mountain-ranges lying transverse to the paths of winter storms, it may be necessary to limit the choice of records still further. Consideration should be given to the origin and normal direction of approach of winter storms, the major topographic features, prevailing winds and temperature during and following storms, etc.

If precipitation-stations are not available within or immediately adjacent to the basin, it is usually possible to establish the limits of a precipitation-region of larger size within which annual variation is more or less the same and, from a study of all available records within the region, to establish indices of seasonal wetness which can be applied to all drainage-basins within the region. In carrying out such a study only the longer records should be used, and investigation should be made to determine whether important changes in gage-exposure have occurred during the life of the record. Some of the longest records in California, such as San Francisco nd Sacramento, have been vitiated for such use because of gage-locations having been changed rom the ground to buildings of progressively-increasing height.

No long-term records--Coming finally to the situation where no adequate past records of any ind are available from which a normal can be established, it is advisable not to state a normal. The first year can be used as a standard and the snow-cover of following years can be temporarily referred to it until such time as a more accurate standard can be established.

Future of area-method--Although seldom practical for use today, the area-method has inherent merit and with increased understanding of the processes involved in watershed-losses and the future accumulation of data, will ultimately come into favor. The writer has for a number of years been making a study of watershed-losses under the wide range of conditions existing along the Pacific Coast from British Columbia to Lower California. These studies have been directed to the establishing of quantitative values for annual watershed-losses applicable to various evaporation-rates, vegetation-types, geological formations, etc. These studies, in addition to giving quantitative results, suggest a simplified method of computing watershed-losses which will eliminate many of the assumptions which are now necessary. It is believed that, as the result of studies such as these, the technique of the area-method can be improved to the point where it will be of practical use.

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LAMOILLE CREEK BASIN NORMALS: A CASE IN WHICH EXTENSION OF NORMALS BY COMPARISON WITH PRECIPITATION-DATA PROVED MORE VALUABLE THAN BY COMPARISON WITH ANOTHER STREAM

Carl Elges

Normals for snow-courses having only a few years record, can be computed by expanding the mean for the period of record by comparison with precipitation, runoff, or an adjacent snow-course for which longer records are available. Those of runoff may be expanded by comparison with precipitation, snow-cover, or with the runoff of an adjacent stream. In the future, tree-ring studies will probably play an important role in the expansion of normals.

In this paper a case is exemplified in which the snow-cover normal was created by comparison to precipitation, and the stream-flow mean was likewise expanded after the available records were carefully analyzed. No special study was made to select a certain case for this paper. A system of normals was wanted for Lamoille Creek in eastern Nevada and therefore this stream was selected for the study here given.

Before proceeding it is well to state that the word "normal" as used means merely a comparative index and not the mean of a period of record as used by the United States Weather Bureau nor the probable average sometimes used by men studying tree-rings or the supposed cycles of weather. The word "mean" is used wherever the figure given is the average of the period of record. Whenever the mean is altered in any way for comparisons to other figures, the word "normal" is used. The writer believes that the average of a period of years gives the best results for comparisons. However, when the records do not cover the same years, the percentages of the means are not comparable and some adjustment is necessary so that the percentages of their adjusted means are brought into balance. These adjusted means are here called "normals".

The Lamoille Creek Basin contains about 15,000 acres of land ranging from an elevation of 6300 feet, where the stream gaging- and precipitation-stations are located, to about 11,500 feet. The snow-courses are located at 7400 and 9000 feet, the lower one being about two miles from the precipitation-station and the upper one about 14 miles. Of the total area, 10,400 acres are above an elevation of 8500 feet and the remaining area of 5400 acres is below 8500 feet.

The following continuous data are available: Precipitation, 1911 to 1935; snow-cover, 1926 to 1935; and runoff, 1932 to 1935. Notice that the runoff-record is the shortest. This is the reverse of the usual case where the runoff is longer than the snow-cover record.

Before any comparisons were attempted a careful study of the data on hand was made. It was discovered that the Lamoille precipitation-station was not always at its present location. Not until 1916 was the station moved to Lamoille. Before that time it was at Lee and Blaine, both at a lower elevation and some 20 miles from the present station.

Table 1

Station	Average precipitation		Percentage precip. (B) to that of (A)
	(A) 1911-35	(B) 1911-15	
Elko	8.38	8.91	106.3
Lamoille	15.94	12.99	81.5

In Table 1, when compared to the precipitation at Elko, a nearby station having a 57-year record, the precipitation for the so-called Lamoille station was nearly 25 per cent lower than that at Elko in terms of their means for 1911-35. This gave sufficient evidence that the figures for 1911-15 would have been higher if the station had been located at its present site during these earlier years. Because of this discrepancy, the usable precipitation-data were reduced to the period 1916-35.

The parallel continuous records for snow-cover, runoff, and precipitation were tabulated, all in percentages of their mean, as shown in Table 2. The runoff for the season of 1933, for which both the snow-cover and precipitation were below, was nearly twice as great as that of the season of 1932 which had all factors above the mean. This supported prior belief that the runoff-record for 1933 was faulty. However, without additional proof the runeff-record for that year could not be discarded. This led to the following quantitative study in which the following assumptions were made: First, that the ratio of the precipitation during spring and summer to the snow-cover present on March 1 was the same as the ratio of precipitation of March-July to November-February at the weather-station. Second, that the water-content on the 9000-foot elevation snow-course represented the average over the 10,400 acres for which it is indicative and, likewise, the 7400-foot elevation course water-content represented the average depth over the 5400 acres in the lower zone.

Table 2

Year	1932	1933	1934	1935
Snow-cover				
7400 ft	133.2	92.8	92.8	81.0
9000 ft	146.0	96.6	78.4	78.9
Precipitation in inches				
March-July	135.3	93.8	58.6	112.3
Runoff in inches				
April-July	105.1	190.0	34.3	70.7

Table 3

Year	1932	1933	1934	1935
Snow-water content, acre-inches				
In upper zone	260000	172016	139672	140400
In lower zone	67338	46926	46926	40932
Total water present March 1	327338	218942	186598	181332
Ratio precipitation March-July to that November-February	1.245	1.218	0.802	1.900
Acre-inches of water added by precipitation	407539	266671	149652	344531
Total water on basin during season				
Acre inches	734877	485613	336250	525863
Acre feet	61240	40470	28020	43820
Measured runoff	39500	71300	12900	26600
Yield in per cent	64.5	176.2	46.0	60.7

Table 3 showed that the yield from the Basin for the seasons 1932 to 1935 inclusive, were 64.5, 176.2, 46.0, and 60.7 per cent respectively. A yield of 176.2 per cent of the water that was deposited on the Basin during any season is of course impossible. Therefore, the season of 1933 was disregarded in comparisons involving runoff. Consequently, the parallel record of runoff, snow-cover, and precipitation was cut to three years.

With the question of available data settled, a comparison of the parallel figures covering the period of record of the snow-courses was then made to determine the best way to expand the short-time mean to a normal.

Figure 1 showed conclusively that the best expansion could be accomplished by comparing the snow-cover at 7400 feet of March 1 with the November-February precipitation. The average snow-cover water-content, 8.11 inches, was divided by the ratio of the November-February, 1926-35, precipitation to that of the November-February, 1916-35, precipitation thus giving 8.47 inches as a normal for the 7400-foot snow-course. The average ratio of the water-content on the 9000-foot course to that on the 7400-foot elevation course was 2.078. At this same ratio the normal for

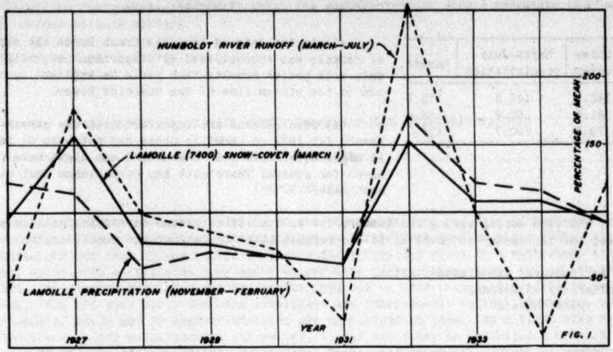

FIG. 1

the 9000-foot elevation course was set at 17.60 inches.

The next problem was to determine whether the stream-flow normal should be based upon the precipitation of 1916-35 or upon a similar period of runoff for the Humboldt River. From the comparative study in Table 4 of the Humboldt River and the Lamoille Creek stream-flow for the three years in terms of their means, two out of the three years showed differences of over 40 per cent. This certainly would not give very reliable results upon which to expand the Lamoille mean.

Table 4

Year	Runoff	
	Humboldt	Lamoille
	per cent of mean	
1932	195.8	150.2
1934	6.5	49.0
1935	97.7	101.1

A comparison of the snow-cover and the runoff for the three years of parallel record showed that the rain during spring and summer had a tremendous influence on the runoff of the stream and unless taken into consideration in the comparisons, the figures for the respective years would not correlate well. Therefore, the comparison was made using the snow-cover present on March 1 plus the precipitation that fell during the runoff season. The figures that were calculated are given by Table 5 in acre-foot units. The amount of water present on the watershed during the season should bear a relationship to the amount that will flow from this watershed. However, it is believed that if a reasonable constant amount is subtracted from the totals, assuming that this constant goes to basin-losses such as transpiration and evaporation, the remainders would be much better indicators of runoff than the original totals. On this basis, 12,000 acre-feet were deducted from the totals. The resulting figures are given by Table 6 in percentages of their means and compared to the measured runoff. These figures gave a much closer correlation than was anticipated and should justify expanding the mean runoff to a 20-year normal by comparison to the November-July precipitation rather than by comparison to the runoff of the Humboldt River.

Table 5

Year	1932	1934	1935
Total water present on watershed (March 1 snow plus precipitation)	61240	28020	43820
Measured runoff	39500	12900	26600

Table 6

Year	Water present on Basin[a]	Measured runoff
1932	152.2	150.2
1934	49.5	49.0
1935	98.3	101.1

[a] Amount having greatest effect toward producing runoff.

The three years for which the parallel records of stream-flow and of precipitation were available averaged 115.4 per cent of the 20-year mean. Assuming that the runoff was 115.4 per cent of its normal would fix the normal at 22,790 acre-feet.

The final results in which all figures are in percentages of the normals which are based upon precipitation during 1916-35 at Lamoille are tabulated in Table 7.

Table 7

Year	Snow-cover	March-July precipitation	Runoff
1932	143.1	145.5	173.3
1934	81.6	62.9	56.6
1935	79.3	120.7	116.7

Conclusions

(1) In the case of Lamoille Creek Basin the expansion of normals was accomplished by comparison to precipitation-data with better results than could be expected by comparison to the stream-flow of the Humboldt River.

(2) Good records are important. If the stream-flow record for 1933 on Lamoille Creek had not been so far off, it might never have been discovered and might have raised havoc for several years with any comparisons that might have been made.

(3) The rain during spring and summer, due to its effectiveness toward producing runoff, will keep the forecaster in doubt as to his results until the end of the runoff-season.

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EXTENSION OF NORMALS BY PRECIPITATION-DATA AND BY COMPARISON WITH ANOTHER STREAM

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The factors affecting relationship between precipitation and consequent runoff are multitudinous and their interrelation is exceedingly complex. They vary widely from time to time and place to place. Basic data are meager and the weight to be given to any single factor is usually uncertain. Runoff-characteristics of drainage-areas within the same region will frequently be quite dissimilar. Under these circumstances no one should hope to answer conclusively paragraph V(a) of the questionnaire submitted January 4, 1935 by the Conference.

Perhaps the greatest obstacle in the way of effective "extension of normals by use of precipitation-data" will be the scarcity of precipitation-records in the mountainous regions of the Western states. Those regions generally have a higher unit-yield of runoff than the low-lying areas and will probably include most of the drainage-areas from which estimates of runoff are desired. In localities where snow-accumulation gradually increases during the winter, with little or no melting from November to March, a better relationship between precipitation and runoff is obtainable than in regions like the Pacific Northwest where a considerable part of the precipitation during winter is in the form of rain and where, during the winter, warm humid chinook-winds often melt some or most of the accumulated snow-fall.

The use of precipitation-records as a basis of estimating runoff also has limitations where large variations in precipitation occur within short distances. For example, the maximum annual precipitation in the State of Washington is nearly thirty times greater than the minimum annual. Moreover the maximum annual, as estimated from precipitation and runoff-records, is about 200 inches on the westward slope of the Olympic Mountains near their crest, whereas 50 miles northeastward in the "rain-shadow" of the Olympics, the precipitation is only about 17 inches. Similar, but less striking variations occur in other parts of the State. Obviously estimates based on either records of runoff or of precipitation are subject to great uncertainty.

The monthly, and even seasonal, relationship between precipitation and runoff in the State of Washington is so erratic that "extension by comparison with another stream to a short record of runoff" is usually preferable. The derivation of runoff from records of precipitation in that State is used only as a last resort. Even then probably the best procedure would be to use a combination of the two methods mentioned in question V(a) as follows: First, estimate annual runoff for climatic years on the basis of measured or assumed annual precipitation, using a short runoff-record as a guide, then prorate it among the months, or the seasons, in accordance with measured runoff at the nearest comparable gaging-station at which records for ten years or longer are available.

Under the most favorable circumstances runoff estimated by either of the two methods, or by a combination of the two, will be far less satisfactory than actual runoff-records. Therefore, the urgency of maintaining gaging-stations at strategic sites within the area to be served by snow-

surveys should be recognized. If practicable, the gaging-stations should be established many years in advance of snow-surveys.

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SOIL-ABSORPTION AND ITS EFFECT ON STREAM-FLOW FORECASTS IN UTAH

George D. Clyde

Introduction

The relationship between precipitation on and the runoff from mountain-watersheds has been the object of intensive study at the Utah Agricultural Experiment-Station since 1923. Although approximately 80 per cent of the runoff available for irrigation comes from watersheds above 7000 feet, which area constitutes only about 20 per cent of the State, there was in the beginning little information available concerning the physical or meteorological conditions on these watersheds. For the most part, the high watersheds are inaccessible during the winter, except by snow-shoes or skiis and no weather-stations are maintained on them. As a first step in a study of precipitation-runoff relationships, therefore, it was necessary to establish a network of snow-courses for measuring the accumulated snow-cover. Such a network of snow-courses, similar to those previously established by Dr. J. E. Church in Nevada, was established on the Logan River Watershed. After seven years of intensive work on this area the network was expanded to cover all of the principal watersheds of the State.

The Utah Cooperative Snow-Survey Network now consists of 80 snow-survey courses established on the six principal watersheds of the State. Most of the courses are located at elevations above 8000 feet. A few are as low as 6000 feet, and records at valley precipitation-stations are utilized in connection with snow-surveys in order to determine the effect of precipitation on the area below the line of winter melting. Cooperating parties in the Utah Network are: (1) Utah Agricultural Experiment-Station, in charge of investigations; (2) Utah State Engineer, cooperating in financing snow-surveys and in making stream-flow forecasts; (3) United States Forest Service, cooperating in making snow-surveys; (4) and the United States Weather Bureau in supplying general precipitation and temperature-data and in publishing snow-cover records. In 1935 the Division of Irrigation of the Federal Bureau of Agricultural Engineering became a cooperator in Utah as well as in all other western states and is now furnishing some equipment and financial assistance for making snow-surveys; it will also act as central agent in coordinating stream-flow forecasts throughout all western states. In Utah, the Agricultural Experiment-Station heads up the cooperating groups within the State; it, in turn, cooperates with the Federal Bureau of Agricultural Engineering. The plan of cooperation in effect in Utah has proved highly satisfactory, and it is believed that cooperation of State with a Federal agency such as the Bureau of Agricultural Engineering, which is charged with coordination of work in the several states, will materially increase the usefulness of results obtained.

Basic factors affecting relationships of stream-flow to runoff

It was early recognized that precipitation-runoff relationships were complicated ones. The causal factors are many and they operate in many different combinations. It is believed that every watershed should be treated as a law unto itself and detailed relationships determined for each. In spite of the foregoing statement there are certain fundamental factors common to all watersheds and certain basic principles that may be established. The principal causal factors affecting the precipitation-runoff relationships may be listed as follows:

(I) Precipitation--(1) Kind: Rain, snow, hail, etc; (2) amount and its distribution; (3) accumulation in the form of snow; (4) precipitation in fall; (5) precipitation in spring, (a) on bare ground and, (b) on continuous snow-cover; (6) watershed-characteristics including (a) vegetal cover, (b) earth-mantle, (c) geological formation, (d) topography, and (e) exposure; (7) Temperature, (a) during snow-accumulation, (b) during melting period, and (c) effect on earth-mantle prior to snow-accumulation; (8) absorption as related to (a) condition of earth-mantle at the beginning of snow-accumulation, (b) moisture-holding capacity, (c) permeability of soil, (d) rate of melting, and (e) vegetal cover.

Of these many causal factors affecting runoff, I wish to direct a few remarks toward absorption as it affects precipitation-runoff relationships. There are numerous discussions in published literature concerning absorption-rates and the mechanics of absorption from rain or surface-streams.

I have been unable to find any information pertaining to total absorption from a snow-cover or to that portion of the water absorbed which ultimately finds its way back to the streams and becomes a part of the usable yield of a watershed. A few general observations and some quantitative measurements may be of interest in this connection.

In 1928 a detailed study of snow-melting characteristics in a small closed basin on the Wasatch Plateau (elevation, 9000 feet) was made by the Utah Agricultural Experiment Station. The runoff from the snow-cover was early and rapid--so rapid, in fact, that the upper two feet of soil quickly became saturated to a point that the entire area was a bog. When the snow-cover was still 12 to 18 inches deep over the area, horses mired wherever they stepped off the packed trails and the steepness of the slope seemed to make little difference. Water was oozing out of the ground everywhere. Quickly following the disappearance of the snow-cover, the ground began drying up, springs dried up, and an early low-water flow was experienced.

Similar observations were made on the same area during 1929. The melting period this year was characterized by colder temperatures interspersed with warm spells. The melting was much slower. At no time did the ground under the snow become saturated and soft for more than six inches in depth. The melting seemed to be at a rate not much greater than the rate of absorption. There seemed to be a greater continuous downward movement of moisture than was apparent in 1928. The saturated soil in 1928 seemed to make the surface impervious to more water and forced a quick runoff to the streams while the reverse was true in 1929. Numerous landslides during this latter year was another evidence of deep penetration which resulted from a slower rate of melting. In 1928 the net yield was 73.7 per cent of the water-content of the snow-cover, while in 1929 it was only 63.4 per cent. These observations indicate that a much greater loss from absorption can be expected in years of retarded melting than in years of quick rapid melting.

The experience of 1933-34 further emphasizes possible loss due to absorption. The fall of 1933 in Utah was exceptionally dry. The early snows were deposited on a dry soil. The abnormally mild winter took the light snows off the lower elevations but left the fairly heavy cover on the higher levels and a high snow-line. At the end of the precipitation-season there was a fairly high accumulation on the higher levels with no low snow. Based on high-snow measurements, the runoff should have been about 40 per cent of normal. The dry ground under the high cover and the absence of low snow so increased the loss, both from the snow-cover on the high areas and from the spring rains on the bare low areas, that actual runoff was reduced in many cases from 40 to 18 per cent of normal. It is believed that this reduction in runoff was at least partly a result of increased absorption.

During the past year an attempt has been made to determine quantitatively the absorption of moisture from the snow-cover and its probable effect in reducing runoff. Soil-sampling plots were located along several widely separated snow-courses. Sites were selected wherever possible to allow a 5-foot sample to be taken.

Soil-moisture determinations were first made on June 4, 1935, after the snow-cover had receded to about 7500 feet in elevation. The first measurements were made at 7000-, 8000-, and 9000-foot elevations and to depths of 5, 4-1/2, and 2-1/2 feet, respectively. The depth was limited in each case by rock or hard-pan. Samples were taken at each foot of depth and the average moisture-percentage at each location, as determined, was 36.4, 26.9, and 40.2 for the respective elevations. The ground was bare at 7000 feet. At 8000 feet the sample was taken under two feet of snow in the timber where little melting had taken place. At 9000 feet the sample was taken under about 20 inches of snow in an open park where there had been considerable melting.

On September 16, 1935, another series of measurements was made over these same courses as well as at three other courses located about 15 miles apart at elevations of 6250, 8200, and 8300 feet. At this time the soil was so dry that samples could not be obtained with a soil-auger below one foot. The moisture-content in the first foot varied from 11 to 14 per cent at the different courses.

On December 7, after the ground had become covered with snow, another set of samples was taken. Fall-precipitation had been abnormally low. Samples were taken each foot. The average moisture-content in the first foot, at each station, varied from 11.3 per cent at the lowest to 19.4 per cent at the highest elevation measured. Below the first foot in all cases the moisture-content averaged between 10.2 and 12.7 per cent.

These field-measurements would indicate that the moisture-content found on June 4 approached the field-capacity. The moisture-content found on September 16, after an extremely dry summer, approached the minimum ordinarily found. The difference in the moisture-content at field-capacity and that found on September 16 converted to inches depth of water equals approximately four inches per foot depth of soil.

Measurements made on December 7 showed that except for the first foot of soil the moisture-content was only slightly greater than on September 16. Based on an average moisture-content of 12 per cent on December 7, 1935, approximately 3.7 inches of water per foot of depth will be required to prime the soil under the snow-cover before any material runoff will take place, unless rate of melting exceeds the rate of permeability of the soil under the snow. For an average 2-foot depth of earth-mantle this would require 7.4 inches of water to prime the soil. The limited number of measurements, together with general field-observations, indicates that the soil-absorption factor is highly important and should be studied further.

The wide differences in soil-conditions on a single watershed or on different watersheds is recognized, but it is believed that if the physical characteristics of the earth-mantle for a given watershed are known the absorption-factor for that watershed can be quite accurately determined.

Conclusions

Summarizing, general field-observations and the quantitative measurements available indicate:

(1) That the absorption-loss from year to year is neither a constant quantity nor percentage.
(2) That it is a function of (a) permeability of soil at the beginning of the melting season, (b) percentage-moisture in soil at beginning of the melting season, (c) water-holding capacity of the soil, and (d) rate of melting of the snow-cover.
(3) That during years of light snow-cover, the percentage-absorption is much higher than during years of heavy snow-cover.
(4) That soil-moisture determinations under the snow-cover at the beginning of melting period may furnish an absorption correction-factor which will prove valuable for use in making stream-flow forecasts.

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THE ADIRONDACK SNOW-SURVEY

E. S. Cullings

The Adirondack Snow-Survey was organized a few years ago in an effort to improve the operation of storage-reservoirs for water-power, navigation, and municipal water-supply in the Adirondack Region and adjacent territory. It is a voluntary, cooperative enterprise, participated in by the engineering staffs of various power-companies and State, Federal, and other governmental agencies.

The Adirondack Region includes an area of about 12,000 square miles in northern New York, having a length of about 140 miles north and south and a width of about 100 miles east and west. The topography is rugged, but hardly mountainous when compared with the mountains of the western part of the country. The highest peak is only about 5300 feet above sea-level, and the average elevation of the plateau does not exceed 2500 feet. Most of the area is densely wooded, with both coniferous and deciduous trees. An excellent system of paved roads covers the entire Region, and these roads are usually kept open to traffic through the winter.

The drainage-system comprises about a dozen streams which flow in all directions from the central highland. The rugged topography and steep grade of these rivers provide numerous water-power sites, the best of which have been developed by the paper and electric-power industries.

The Adirondack Region has a temperate climate, the mean annual temperature being about 40° F. The air-temperature seldom reaches 100° F in summer, but it frequently falls as low as 50° below zero in winter. A record low of 60° below occurred in January 1934. The rainfall varies from 40 to 50 inches and, generally speaking, it is well distributed through the year. There are no pronounced wet or dry seasons, but wet or dry periods of varying length occur at irregular intervals. The runoff amounts to from 50 to 60 per cent of the precipitation. Between December 1 and April 1, most of the precipitation is in the form of snow. Because of the timber there is little drifting and the snow accumulates in a uniform blanket having a depth of from three to five feet and a water-content of from six to 12 inches at the end of the winter. Figure 1 shows the normal accumulation of snow at Hoffmeister. The Region lies in the north temperate storm-belt, and the prevailing winds are westerly. The ordinary storms are of the cyclonic type, except during the summer, when thunder-storms are frequent. Storms causing from two to three inches of precipitation occur quite frequently (nearly every year) but storms in excess of five inches are quite rare.

Because of the industrial development of this Region, the water-powers are of considerable importance. The water-resources are carefully guarded, but have not yet been fully developed. Records of the flow of all the principal streams have been maintained by the United States Geological Survey for many years, and about 25 precipitation-stations are maintained in this Region by the United States Weather Bureau and cooperating agencies.

The measurement of snow in a systematic manner was begun about ten years ago by the engineers of the Black River Regulating District, in connection with the operation of a system of storage-reservoirs. In the earlier years the work was limited to the watershed of the Black River, which lies on the westerly side of the Adirondack Plateau, but with the aid of other interested parties the surveys have been extended until, in later years, practically all of the central plateau has been covered with some degree of completeness.

Snow-surveys are usually made on or near February 1, March 1, and about the third week in March, at which time spring melting usually begins. In the ordinary season, most of the snow has melted by the end of April. Each cooperating organization covers the area in which it is primarily interested. The surveys follow the methods developed by Dr. James E. Church of the Nevada Agricultural Experiment Station. Courses are laid out at intervals of ten or 15 miles in

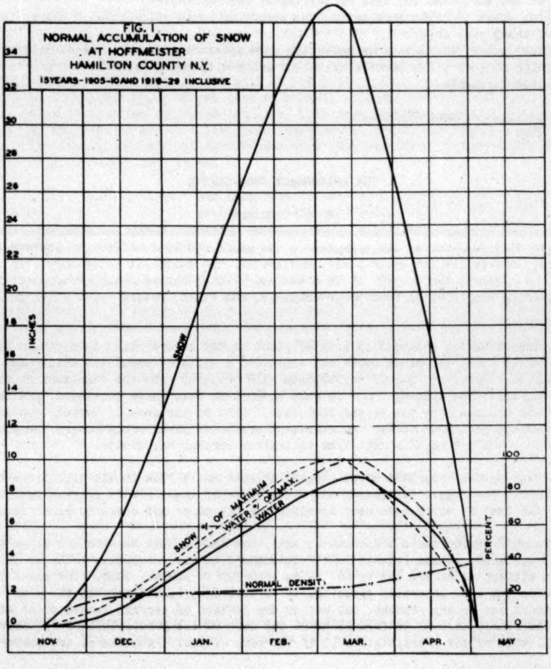


FIG. 1
NORMAL ACCUMULATION OF SNOW
AT HOFFMEISTER
HAMILTON COUNTY N.Y.
15 YEARS-1905-10 AND 1919-29 INCLUSIVE

reasonably level, wooded territory which lies as close as practicable to the highways. A course usually consists of five points about 100 feet apart. Two measurements are made at each point, or ten for the course, and these are averaged for the course-depth. The depth and water-content are measured in the field, and the density is computed. Snow-stakes are maintained at a few of the courses where observers are resident through the winter and readings are made weekly.

The equipment consists of snow-tube, scale, hook, note-book, and canvas bag, and, in addition, such personal equipment as snow-shoes, pocket-knife, compass, and small axe. Some of the observers also take temperature-readings of the air and snow, which requires a thermometer and shovel. Measurements of ice-thickness and water-temperatures in the lakes have also been made.

The snow-tube used in this Region is a 3-inch duralumin tube from four to five feet long, equipped with a steel cutter in one end and a hardwood plug in the other. Cutters have been made from specially tempered steel, phosphor bronze, and plain steel pipe. The latter has been found to be the cheapest, most durable, and most generally satisfactory. The cutter is of such size (2.655 inches in diameter) that ten inches of water will weigh two pounds. This permits the use of a commercial spring-balance which weighs six pounds in three revolutions of the dial. The balance is provided with a special brass or aluminum dial graduated in 100 equal parts representing 10 inches of water per revolution. The water-content to the nearest tenth of an inch can thus be read directly from the scale. The empty tube will weigh about two pounds, requiring one revolution of the dial and, as the water-content of the snow seldom exceeds 10 or 12 inches, the 6-pound, 3-revolution scale has sufficient capacity for any snow-sample to be found in this area.

In weighing a sample, the scale and tube are hung from the limb of a convenient tree or from a forked stick cut at the site. The tube is supported by a two-pronged hook made from about two feet of gage No. 5 or No. 6 aluminum wire. This wire is light, pliable, and easily bent to fit the tube. Moreover, it can be folded up and carried in the bag or pocket. The duralumin tubing is obtained from the Aluminum Company of America at a cost of from 35 to 40 cents a linear foot, at the factory. The cutters are made in a local machine shop at from four to five dollars each. The scales are manufactured by John Chatillon and Sons of New York City. The aluminum wire comes from the stock-room of the nearest electric company. Specially printed, loose-leaf note-book sheets are used in canvas covers manufactured by Asa L. Shipman's Sons.

The Chairman of the Survey usually suggests the date on which a survey should be made and notifies the participating parties, each of whom covers his own territory, usually by automobile, covering the selected area in about two days. The snow is usually soft, of uniform density, and there is seldom any difficulty in getting a good sample. Under ordinary conditions, there is no frost in the ground in the wooded areas where the snow is two feet or more in depth. Occasionally, however, the ground freezes before the snow comes, or the first storm of the winter will be in the form of rain which freezes at the ground-surface and forms a layer of ice, but this does not often happen.

Ordinarily, the cutter will pick up a "plug" of leaves and forest-duff. This material must be carefully removed with a twig or knife-blade before weighing. The empty tube is weighed each time before a sample is taken, and the weight of the sample is determined by subtracting the weight of the empty tube from the weight of the loaded tube. The outside of the tube is graduated in inches, from which the depth of the snow can be read directly. No shellac or other treatment of the tube-surface has been found necessary.

In this area the snow-cover is ordinarily so uniform that the quantity of water stored on the ground in the form of snow can be computed directly from the survey-measurements, and it is unnecessary to resort to calculations made from percentages of normal. In a given reservoir-area it is thus possible, with a few well-distributed measurements, to estimate with a reasonable degree of accuracy the quantity of water available for filling the reservoir at any given time. At most Adirondack courses the period covered by the record is too short for the calculation of satisfactory normals, but it is our intention to undertake a study of normals as soon as ten years of dependable records are available. It is believed that a study of normals will be of considerable value in estimating losses due to evaporation and sublimation, which, under certain weather-conditions, may amount to a considerable part of the accumulated snow. Another "loss" is seepage into the ground but, as the underlying rock is impervious, this loss is only temporary and it soon reappears as ground-water discharge.

At the conclusion of each survey, the observers send their notes to the Chairman, who tabulates the snow- and water-depths and plots the results on a small map of the Adirondack Region. If sufficient measurements are available, isohyetal lines are drawn. Copies of the report and map are sent to each of the participating parties.

In conclusion, it seems desirable to call attention to the importance of ground-water observations along with snow-survey work. As yet, the possibilities of correlating ground-water stages with snow-data have been only partly explored. In this Region a large part of the flow of the streams is derived from ground-storage, rather than surface-runoff. In the areas of glacial sand, much of the melting snow seeps into the ground and later appears as ground-water discharge. It has been noted that, in certain years, only about half the accumulated snow at the end of the winter could be accounted for as surface-runoff in course of the flood in spring. It seems probable that an intensive study of normals, as applied to snow, ground-water, and stream-flow, will be of considerable value in correlating these phenomena and in estimating the water available for future use.

Black River Regulating District,
Watertown, New York

APPENDIX A--INSTRUCTIONS TO OBSERVERS

Purpose--The purpose of a snow-survey is to determine the quantity of water stored upon the ground in the form of snow at any given time. This information is of particular value in the operation of storage-reservoirs for river-regulation and water-power, and it should be useful in the operation of reservoirs for domestic water-supply and other purposes. A knowledge of the accumulation of snow at the end of winter is also of value in forecasting the possibility of floods.

Procedure--For the Adirondack Snow-Survey it is recommended that the survey-methods developed by Dr. J. E. Church and Professor H. P. Boardman of the University of Nevada be followed as closely as practicable, with such modifications as may be necessary to adapt them to Adirondack conditions. Briefly stated, the procedure is to lay out "courses" in representative regions and measure the depth and weight of samples of the snow on the ground at several points in each course. The equivalent depth of water is computed from the weight of the samples. The average of the measurements at the several points in a course is assumed to be the average for that locality, and the average of the several courses should represent the average for the region covered.

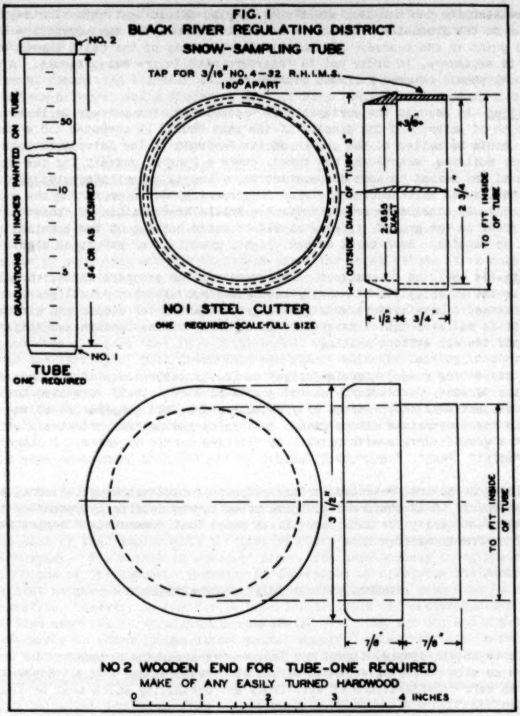
Equipment--The equipment necessary for a snow-survey consists of a snow-sampling tube and a weighing-scale. The sampling-tube consists of a 3-inch tube of aluminum alloy about four or five feet long, in one end of which is fixed a "cutter" of hardened tool steel of such diameter, relative to the weighing-scale, that the scale-graduations represent inches, or decimal parts of an inch, of water. In the other end of the tube is a plug or disc of wood which may be used for pushing the cutter down through the snow in taking a sample. A dimension-sketch for a snow-tube is attached hereto (Fig. 1).

The scale recommended is a spring-balance manufactured by Chatillon and Sons, New York, having a total capacity of six pounds in three revolutions at two pounds per revolution. The dial is graduated in 100 equal parts, representing ten inches of water when used with a cutter having a diameter of 2.655 inches. A convenient loose-leaf note-book is manufactured by Asa L. Shipman's Sons, New York (No. 82804).

Tubes and scales are easily damaged and should be handled with care. The scales should be checked occasionally for accuracy. A small file carried in the note bag will be found useful for sharpening the cutter if it is accidentally damaged.

In each district to be surveyed, a sufficient number of snow-courses should be located early in the season. It is recommended that each course consist of at least five points about 100 feet apart, in a reasonably straight line, if practicable. The course, however, should be modified to fit the topography and might in some cases surround a definite area, especially if a considerable number of points are to be measured. The course should be representative of the locality, free from drifting snow, and as conveniently accessible as possible. Generally speaking, courses in hardwood timber will be most satisfactory, as the trees will prevent drifting, but will not intercept any material quantity of snow in the leaves and branches, as will be the case with soft-wood or evergreen trees. Distribution of snow in soft-wood timber is not uniform. Swampy areas should be avoided. The course should not have either a pronounced southern or northern slope. If reasonably level ground is not available, the course should include points on both northern and southern slopes. It will facilitate the work if the courses are laid out as near to open roads as practicable, but all points should be far enough away from the road to eliminate the drifting of snow from the road on to the points measured. In general, courses

FIG. 1
BLACK RIVER REGULATING DISTRICT
SNOW-SAMPLING TUBE


NO. 2
TAP FOR 3/16" NO. 4-32 R.H.I.M.S.
180° APART
GRADUATIONS IN INCHES PAINTED ON TUBE
3/4" OR AS DESIRED
50
10
5
3/16"
OUTSIDE DIAM. OF TUBE 3"
2.695 EXACT
2 3/4"
TO FIT INSIDE OF TUBE
NO 1 STEEL CUTTER
ONE REQUIRED-SCALE-FULL SIZE
1/2
3/4"
NO. 1
TUBE
ONE REQUIRED
3 1/2"
TO FIT INSIDE OF TUBE
7/8"
7/8"
NO 2 WOODEN END FOR TUBE-ONE REQUIRED
MAKE OF ANY EASILY TURNED HARDWOOD
0
1
2
3
4 INCHES

need not be closer together than from 10 to 15 miles, but special conditions may require additional courses.

The points at which measurements are to be made should be clearly marked on trees or by stakes, and a small area around each point should be cleared of brush before the snow begins to fall. Snow-stakes, graduated in inches, will facilitate the reading of the depth of snow. Cheap steel fence-posts have been found satisfactory for holding the stakes in position. Measurements should be made in the immediate vicinity of identical points, year after year, in order that normals may be computed. Experience will demonstrate the value of each course, and it may occasionally be necessary to abandon an unsatisfactory course and select a new one.

Measurements--On arriving at the first point in a given course, the scale should be hung up on a stake or on the limb of a tree, ready for weighing the empty tube. The name of the locality, the name of number of the course, the name of the observer, the date and the numbers of the tube and the scale should be entered in the note-book before making an observation. The number of the sample and the depth of snow, if snow-stakes are used, should then be noted. Next the empty tube should be weighed, and the weight recorded; then the tube should be pushed vertically downward through the snow to the ground and slowly withdrawn, with the complete core of snow inside the tube. The bottom of the tube should be inspected, and, if a plug of leaves or soil has been removed with the snow, it should be carefully removed before weighing. The tube with the core inside should then be weighed and the weight recorded. At least two samples should be taken at each point, and the empty tube should be weighed before each measurement. If there is a wide discrepancy between the two samples, additional samples should be taken. The depth of snow should be read on the graduated tube before it is withdrawn. The same procedure should be followed at each point in the course. The snow in the vicinity of the point should not be tracked up more than is necessary, in order not to interfere with future measurements. A separate page in the note-book should be used for each course.

Computations--As soon as the survey has been completed, the average depth of snow, the equivalent depth of water, and the density of the snow should be computed and a summary of all measurements should be mailed to the office of the Chairman of the Adirondack Snow-Survey (530 Light and Power Building, Watertown, New York), where a general summary for the whole region will be prepared and mailed to each cooperating party and to other interested persons. Notes and explanations, which will be of assistance in preparing and interpreting the summary, should be included. Unusual conditions or circumstances should be explained or comments should be made. The depth of frost in the ground, if any, should be noted. Notes on the physical character of the snow will be helpful. Such terms as new, light, granular, or saturated might be used.

Other data--It would be desirable for observers, so far as practicable, to make notes on such factors as the interception of snow by the leaves and branches of evergreen trees and, perhaps, to make additional measurements in evergreen timber, for comparison with adjacent hardwood areas. It is believed that a material loss of water occurs through such interception and evaporation into the air without melting.

Another interesting subject for investigation is the temperature of the snow at various depths below the surface, particularly at the ground-surface. It is suggested that those interested in this subject make observations of air-temperature, the temperature of the snow at various depths, and the temperature of the ground just below the surface, if it is not frozen. The character of the ground-surface with respect to moisture should be noted. It might be roughly expressed as "moist", "wet", "saturated", etc.

The foregoing notes are presented for the purpose of systematizing the work, and making the notes of all observers truly comparable. Close attention to details is necessary if dependable and comparable results are to be obtained. It is hoped that comments and suggestions for improvement will be freely made.

IMPROVEMENT IN SNOW-SURVEY APPARATUS

J. E. Church

The desire to obtain simple, light, and inexpensive apparatus became one of the insistent motives as soon as snow-surveying expanded beyond its developmental stage. However, resisting these desirables were considerations of efficiency and durability which must be the final standards of choice.

The Mount Rose snow-sampler was developed in the deep snows of the Sierra Nevada where capacity and strength were demanded. On the other hand, the Utah snow-sampler, a variant of the Mount Rose pattern, had its origin in relatively shallow snow where neither capacity nor strength were essential. Since adaptability to all types of snow is eminently desirable, the problem of improvement of apparatus became one of attaining lightness but retaining capacity, efficiency, and strength. Costs must be kept subordinate to these. This seemed also to be the ideal of the Water-Resources Committee of the National Resources Committee which recommended (Report of Special Advisory Committee on Standards and Specifications for Hydrologic Data, August 1, 1935) "a sampler similar to the 'Mount Rose' type..... but lighter than most of those now used, and at the same time sufficiently durable for practical purposes..... For weighing the sampler and snow-core, the 'Mount Rose' balances,..... with an adjustable index, or a balance of similar construction, should be used."

The organization of the Federal-State Cooperative Snow-Surveys for the Western States and the urgent need of standard or, if possible, uniform apparatus gave impetus to further investigation which had been slowly progressing. The Nevada Agricultural Experiment Station, the pioneer in snow-surveying and the developer of the Mount Rose snow-sampler, authorized a project on the Improvement of Snow-Survey Apparatus and placed it under the Adams Act which had made the original pioneer work possible.

Wide cooperation was sought for the project and much indirect assistance was derived from the increased activity in snow-surveying. The United States Bureau of Agricultural Engineering had ordered apparatus combining features of both the Mount Rose and Utah samplers and its manufacture by Julien P. Friez and Sons, Baltimore, gave an insight into the difficulties of "quantity-production."

J. C. Stevens, Consulting Engineer and designer, of Portland, Oregon, undertook the development of a springless balance, while Frederick Herz of Reno, Nevada, and Hansen Machine Works of Sacramento, California, developed methods of construction.

Duralumin versus steel

(1) Distortion of metal in working--The problem centered mainly around the possibility of using duralumin, which had been adopted as a light, yet strong, material for the Utah sampler. This fundamental change should be credited fully to Professor George D. Clyde, Utah Agricultural Experiment Station, who had long urged the use of this metal.

The advantage of duralumin was its lightness since for equal volume it is only one-third as heavy as steel and is only slightly more expensive; for example, in May 1936 relative cost of steel tube of outside diameter 1-3/4 inches and No. 20 gage is to that of duralumin tube of same diameter and No. 18 gage as 53 to 65. However, the tendency of duralumin to expand under the pressure of tooling caused the tubes to acquire convex curvature opposite the slots and graduations to so pronounced a degree that in a total length of 17.5 feet the axis of the sampler was five inches from the vertical. This distortion was almost entirely lacking in steel tubing but seemed unavoidable in duralumin. Friez and Sons suggested staggering the sections of the sampler to equalize the convexity. However, the resulting lack of alignment in both the tube and the slots and graduations seemed too high a price to pay for the gain in lightness, since continuity of vision, especially under the strain of sampling, is more important than the saving in weight, except possibly where the sampler is unusually long. The emotional mal-effect of a crooked sampler also is more pronounced than the actual crookedness.

Fortunately, Frederick Herz discovered a feasible method of expanding the concave side of the sampler to correspond with the other, thus correcting the distortion. It consisted merely of stringing each sampler-section upon a steel cylindrical shaft of perfect alignment and kneading the concave side of the sampler with a chisel of blunt edge made concave to fit the cross-section of the sampler. The chisel is advanced slowly but continuously along the section under light but rapid blows of the hammer. Symmetry is determined by revolving the section on the shaft. Only slight roughness results, which can be readily smoothed down with emery cloth. This entire operation, however, is one for an expert with tools and preferably for the manufacturer. The time required to straighten a sampler 17 feet long was one and one-half hours, which must necessarily be added to the other costs. However, relatively considered, this item is small. Carl Elges suggests that a concave roller, fitting the cross-section curvature of the sampler, would save much time and avoid ridging the tube.

(2) Difficulty of uniting parts--The second major problem was the difficulty of soldering the steel cutter into the duralumin tube, or in fact of using heat upon this metal except under expert control. A solder has now been compounded but applies only to welding aluminum alloys, not to welding steel to aluminum. [See Science News-Letter, September 28, 1935 (brought to our attention by Director S. B. Doten, of this Station), which states: "The new welding-material, known as 'Allusol', will join aluminum in cast, rolled, sheet, or tube form and fluxes freely at 200° C, according to the United States Department of Interior's Mineral Trade Notes of August 20, 1935. The method, invented by an unnamed engineer of Coventry, Warwickshire, England, overcomes the old trouble wherein attempts to weld aluminum in ordinary fashion destroyed the effects of the previous heat-treatment. Test-pieces of RR 56 and Hiduminum tubing socketed together and joined with 'Alusol' were only pulled apart at forces of 26 tons to the square inch, leaving the welded joint intact. 'Alusol' is claimed to withstand corrosion well and is unaffected by aging..... It has also been found, the report states, that aluminum tubing can be joined to steel by the method, providing the steel is first tinned with a coat of soft solder. A joint of this character is said to withstand a pull of six tons per square inch."]

However, Herz had discovered that by the simple process of expansion with subsequent contraction of the duralumin tube, the steel cutter can be inserted and held firmly in place by friction alone. So unyielding is the friction that the tube will tear before the cutter is released. Care should be taken to make the collar of the cutter sufficiently small so that undue expansion of the duralumin tube may not be necessary to release it, for extra heat would thereby be necessary.

Because of the danger to the duralumin of using an open uncontrolled flame for the purpose of expanding the metal to change the cutter, experiments have been tried with hot water, then finally with candles. Hot water spread too much to be effective, but a unit of two candles seemed to produce sufficient heat for the necessary expansion of the tube. Fortunately, candles can readily be carried by field-parties, who necessarily must change the cutters. However, unless the expansion fully releases the cutter, a pair of pliers or a hook must be used to draw or drive the cutter forth. The exchange of cutters in the field will be infrequent but, when attempted, must be done without injury.

The use of rivets, as in the Utah sampler, involves the difficulty of removing the rivets to release the cutters. The heat necessary to melt the solder might damage the duralumin and digging out the rivet might expand or disfigure the rivet-hole in the duralumin too greatly.

Couplings can be put on in the same manner as the cutter, except that the couplings themselves are expanded. Thus both solder and rivets can be avoided. The expansion-method has now been tried both in manufacture and in the field and found to be practicable. However, manufacturers must use the method with exactness.

(3) Tendency to "seize"--The friction-tendency of duralumin may become a positive danger unless controlled, for without anti-seize compound the couplings may "seize" or "freeze" so rigidly that the coupling will not release at pressure on the wrenches less than that capable of turning the sampler-tube within its coupling. Thus the driving wrench must be abandoned for the weaker spanner-wrenches which are inserted directly on the couplings themselves. In the one experience so far had with such seizure, two gun-barrel stillson-wrenches were employed to break the joint. Subsequent tests even under conditions of dirt indicated that anti-seize applications to the threads of the joints, if faithfully maintained, would prevent the threads from locking. The anti-seize compound, furnished by Hansen Machine Works, Sacramento, California, and Julien P. Friez and Sons, Baltimore, have the following ingredients: (a) Hansen's anti-seize compound--white lead, vaseline, and zinc dust in equal parts; (b) Friez and Sons' compound--50 per cent of zinc dust and 50 per cent of petrolatum.

(4) Rigidity--In respect to rigidity, duralumin is superior to steel and, therefore, is preferable to the latter for long samplers, where weight becomes burdensome and hampers agility. It was found that a duralumin sampler 20 feet long, filled with snow and held horizontally, showed no tendency to whip as did steel, nor did it sag at the ends even when tossed upward and caught by the hands in the descent. The sampler could also be held vertically by one person without undue effort against a moderate wind, whereas the steel sampler of this length required the vigilant attention of two or, in a heavy wind, even three.

In driving in deep snow, the duralumin tube was found sufficiently strong and rigid to bear the weight of a man of 160 pounds standing on the driving wrench, provided the tube was steadied slightly against bending.

(5) Oxidation--Steel has always been vulnerable to moisture because of its tendency to rust, but was finally protected by a thin coating of Valspar varnish that not only afforded immunity from rust but prevented the snow from adhering readily to the metal.

Duralumin seemed to be free from these tendencies of rusting and adhering to snow, but showed a strong tendency to oxidize whether wet or dry and to soil the hands. Recourse was again had to Valspar varnish which cut down all oxidation and gave comfort to the hands.

(6) Relative and maximum weight--If their volumes were similar, the relative weight of duralumin and steel, as mentioned before, would be approximately 1:3. However, a gage as light as No. 20 has been adopted for steel samplers whereas gage No. 18 is used at present for duralumin. A gage as heavy as No. 16 might increase the durability of the duralumin considerably. The relative weight at various gages is as follows:

Duralumin	Steel	Approximate relative weight
No. 18	No. 18	1:3
No. 18	No. 20	1:2.25
No. 16	No. 20	1:1.8

The absolute weight of the two metals at their optimum gages and at the probable maximum length of 20 feet is given not only for comparison but also for estimating loads: Steel gage No. 20, 17.5 pounds; duralumin gage No. 18, 7.8 pounds; duralumin gage No. 16, 9.8 pounds.

Many samplers will be only six feet long, particularly in the Great Basin. The usual length in the Sierra will be 12 to 20 feet. The usual weight will therefore be correspondingly less than above and only in exceptional cases will it be more, as in the Pacific Northwest where maximum snowfall occurs.

(7) Tendency to bruise--The tendency of duralumin to bruise far more readily than steel may prove to be a deciding factor against its use. When being packed or carried, it must be carefully safeguarded against pressure and blows. In this respect it lacks the hardiness of steel. Only long service under normal rough usage can determine the survival power of duralumin as against steel.

Sampler-features

Practically all of the fundamental features of the Mount Rose snow-sampler were adopted by the United States Bureau of Agricultural Engineering, the only exception being the inside diameter of the cutter. Deviations from the Utah snow-sampler and changes in the Mount Rose sampler are discussed under the following individual heads:

(1) Cutter: (a) Diameter--The cutter of the Utah snow-sampler was given an inside diameter of 1.485 inches in order to make one inch of water weigh one ounce and thus facilitate the use of ready-made or commercial spring-balances. The diameter of the Mount Rose cutter was set at 1.50 inches because of its simplicity and has since been maintained because of the ease of making 15-inch, circular evaporation-pans that could thus be weighed directly to inches of water with the spring-balance used for the Mount Rose snow-sampler. In the rare instances in which the commercial spring-balance has been employed, the recorded weight was reduced by 0.02 to obtain the weight in inches of water. "Because of the number of Utah snow-samplers in use," the Bureau of Agricultural Engineering chose the Utah diameter of 1.485 inches.

(b) Contour--Since the Utah cutter was a chisel and reamer rather than a self-clearing cutter, the detailed features of the Mount Rose cutter were adopted except that the new cutter was made more bulbous to create a larger hole for the couplings. However, the resulting wide shoulder of the cutter became an impediment to withdrawing the sampler--so much so that Herz reported that "it required only one man to drive the sampler but two men to pull it up." The effort sometimes resulted in the loss of the core. The substitution of the original Mount Rose cutter in the duralumin sampler corrected the difficulty (see A of Fig. 1).

(c) Temper--The teeth of the cutter when made too slender and too hard not only broke off but resisted refiling. Consequently the teeth are now made somewhat blunter and the temper is softened to the filing stage, thus greatly extending the life of the cutter. This improvement is fundamental in view of the original high cost of the cutter and the hard wear inevitable in driving on gravel and unseen rocks.

(2) Couplings--A simple sleeve coupling with threads directly upon the duralumin tube was designed for the Utah sampler. Because of the weakness of the walls of the tube, the fineness and frailty of the threads, and their exposure to injury, the Mount Rose couplings were adopted but were made of duralumin in place of steel. At the suggestion of the Hansen Machine Works the coupling was made one-half inch longer at either end to increase its frictional hold upon the tube to which it was attached by shrinkage alone. The coupling also was tapered at either end to eliminate obstruction in driving. The inner shoulders of the couplings and the coarse threads afford rigidity and strength (see B of Fig. 1 and B of Fig. 2). Two spanner-wrenches inserted in holes in the couplings aid in unscrewing the sections.

(3) Length of sections--It was felt that replacement of parts could be greatly facilitated by having sections of standard length, but agreement on the exact length was difficult. In deep snows long sections were preferred if transportation was easy, but difficulty in carrying on back or on horse gradually reduced the length to four feet and even to three feet. Finally, because of the danger of carrying projecting samplers in the low, thick timber of Yellowstone Park and adjacent regions, a standard length of only two and one-half feet was finally but provisionally set. The fear that multiplicity of couplings would unduly obstruct the passage of the sampler through the snow proved groundless, for the passage of the first coupling prepared easy passage for the others. Furthermore, the couplings added to the rigidity of the sampler.

However, the cost of the sampler is proportionately increased; likewise, the chance of locking. On the other hand, there appears to be no automatic machine at present available for slotting and stamping sections longer than 30 inches. Therefore, the longer sections would entail expensive handwork. A major advantage of standardized sections, however long the section, is the ease of extending a sampler to any desired length by adding additional sections. The half or entrant coupling at the top of each section affords a comfortable ferule in driving.

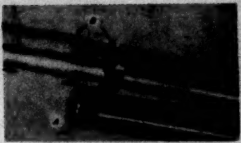


FIG. 1—SAMPLER-TUBE: A=CUTTER; B=OPEN COUPLING SHOWING THREADS

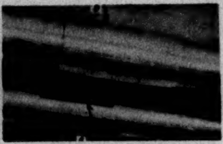


FIG. 2—DURALUMIN SAMPLER-TUBE: A=SLOTS; B=CLOSED COUPLING (LATER DESIGN HAS LONGER MORE GRADUAL TAPER)

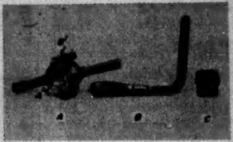


FIG. 3—A=DRIVING-WRENCH; B=CLEANING-HOOK; C=CUTTER; A'=TONGUE; B'=LOCK

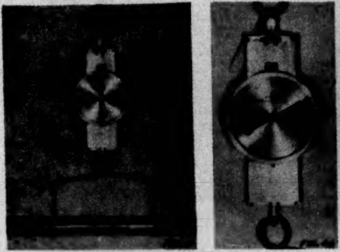


FIG. 4 AND 4A—MOUNT ROSE SPRING-BALANCE [4—READY FOR SAMPLING; 4A—NO. 5 BY LEUPOLD AND VOLPEL]

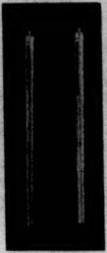


FIG. 5—UTAH TYPE SPRING-BALANCES

[EXPLANATION: THE ONE ON THE LEFT HAS CAPACITY OF 125 WATER-INCHES AND THE ONE ON THE RIGHT WILL WEIGH 105 WATER-INCHES (EXCEPT FOR SMALL INITIAL TENSION EQUIVALENT TO APPROXIMATELY 5 FEET OF EMPTY TUBING, THESE CAPACITIES INCLUDE WEIGHT OF EMPTY SAMPLER SINCE THEY CANNOT BE ADJUSTED TO ZERO BEFORE THE SAMPLE IS WEIGHED)]

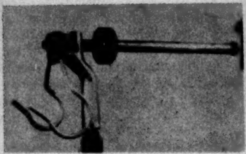


FIG. 7—STEVENS SPRINGLESS SNOW-SURVEY BALANCE BY LEUPOLD AND VOLPEL

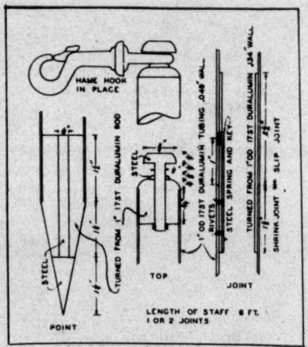

HAME HOOK IN PLACE
STEEL
TURNED FROM 1" 17ST DURALUMIN ROD
STEEL
1" OD 17ST DURALUMIN TUBING .049" WALL
RIVETS
STEEL SPRING AND KEY
TURNED FROM 1" OD 17ST DURALUMIN .134" WALL
SHRINK JOINT
SLIP JOINT
POINT
TOP
JOINT
LENGTH OF STAFF 6 FT.
1 OR 2 JOINTS

FIG. 6—WEIGHING-STAFF FOR USE WITH SPRING-BALANCE

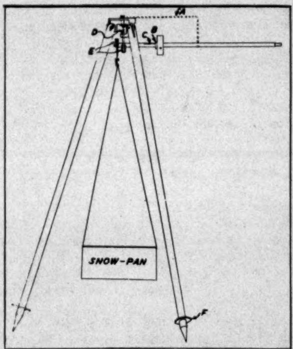

A
B
C
D
E
F
SNOW-PAN

FIG. 8—STEVENS SPRINGLESS BALANCE ON TRIPOD FOR WEIGHING EVAPORATION-PANS

A=PROPOSED DURALUMIN-BAR WITH SUPPORTS TO KEEP WEIGHT-ARM FROM GOING TOO HIGH OR LOW SO THAT THE INSTRUMENT CAN BE MORE READILY SET UP; THIS ARM IS HINGED AT TOP OF TRIPOD AND CAN BE ROTATED HORIZONTALLY TO FREE IT WHEN OPERATOR IS READY TO MAKE FINAL ADJUSTMENT; B=TRANSPARENT SLEEVE CONTAINING INDICATOR; C=GRADUATED ON TOP AND BOTH SIDES OF THE BAR SO THAT IT CAN BE EASILY READ BY EITHER A TALL OR SHORT MAN FROM EITHER SIDE; D=SINGLE-POINT SUPPORT; E=DOUBLE-POINT SUPPORTS; F=DISC TO KEEP LEG FROM SINKING TOO DEEP INTO SNOW

(4) Slots--Slots have always been maintained in the sampler-tube for observing the height of the core and for clearing the tube by means of a cleaning hook in case of adhesions of snow (see B of Fig. 3). The width of these slots was narrowed in the Utah sampler to 1/16 inch to prevent the entrance of snow, but this likewise made their use difficult for breaking up adhesions. Since the slots are used also as the toeholds for the driving wrench, the width of 1/8 inch has finally been adopted (see A of Fig. 2).

(5) Driving-wrench--The Mount Rose driving-wrench is now made of cast duralumin including the handles. Only the lock and tongue are of steel. At the suggestion of the Universal Tool Company, San Francisco, the tongue (see A and A' of Fig. 3) was moved 45° to the base of one of the handles to simplify construction and facilitate insertion of the tongue into the slot of the sampler.

Balances

(1) Dial versus tubular balances: (a) Range and precision--The original consensus of opinion was that the dial or Mount Rose spring-balance (see Figs. 4 and 4A) possessed wide range but lacked delicacy or precision and that the tubular or Utah spring-balance (see Fig. 5) possessed precision but lacked range. The Mount Rose type has now been found to possess both range and fair precision and, in addition, has an adjustable index. The earlier failure in precision was due to friction of the springs against the case, which had been made too narrow in the search for compactness.

In a test in the laboratory, the balance was sufficiently delicate to attain tension with only a single section two and one-half feet long of duralumin-sampler in the cradle, yet with a sampler 250 inches (20 feet 10 inches) long in the cradle and the index set to zero the balance would still retain a measuring capacity of 260 water-inches (21 feet 8 inches). Thus since the density of snow rarely exceeds 60 per cent that of water, there remains a reserve capacity of 104 water-inches to be apportioned between a still longer sampler and deeper snow, actually found the past winter in the Lake Tahoe and Mount Lassen regions.

The results of a test with two duralumin sections of 98 inches (weighing 3.1 lb) in the cradle indicate the relative accuracy in a range of 25 pounds or approximately 400 inches of water. The test, summarized in Table 1, was conducted with an improved model (by Leupold and Volpel) and an old laboratory-model (by S. P. Fergusson). The range is divided into two sections, namely, the lower (1 to 14 lb) representing 20 feet of snow at 60 per cent or maximum density and the higher (15 to 25 lb) representing snow from 20 to 30 feet deep.

Table 1--Test of range and accuracy of Mount Rose spring-balances

Leupold and Volpel balance No. 5				Fergusson balance			
Wt.	Scale-reading	Theoretical scale-reading	Difference	Wt.	Scale-reading	Theoretical scale-reading	Difference
lb	inch	inch	inch	lb	inch	inch	inch
1	15.5	15.67	+0.17	1	16.5	15.67	-0.83
2	31.8	31.34	-0.46	2	31.5	31.34	-0.16
3	47.0	47.01	+0.01	3	47.0	47.01	+0.01
4	62.8	62.68	-0.12	4	63.0	62.68	-0.32
5	78.4	78.35	-0.05	5	78.5	78.35	-0.15
6	94.0	94.02	+0.02	6	94.5	94.02	-0.48
7	109.7	109.69	-0.01	7	110.5	109.69	-0.81
8	125.5	125.36	-0.14	8	126.5	125.36	-1.14
9	141.5	141.03	-0.47	9	142.5	141.03	-1.47
10	157.3	156.70	-0.60	10	158.3	156.70	-1.60
11	173.0	172.37	-0.63	11	174.0	172.37	-1.63
12	189.2	188.04	-1.16	12	190.0	188.04	-1.96
13	204.5	203.71	-0.79	13	205.5	203.71	-1.79
14	220.0	219.38	-0.62	14	221.0	219.38	-1.62
		Mean error	-0.36			Mean error	-0.98
15	236.5	235.05	-1.45	15	235.3	235.55	+0.25
16	252.0	250.72	-1.28	16	252.3	250.72	-1.58
17	268.0	266.39	-1:61	17	268.3	266.39	-1.91
18	284.3	282.06	-2.24	18	284.0	282.06	-1.94
19	300.0	297.73	-2.27	19	300.0	297.73	-2.27
20	316.0	313.40	-2.60	20	316.5	313.40	-3.10
21	331.5	329.07	-2.43	21	331.5	329.07	-2.43
22	347.0	344.74	-2.26	22	347.3	344.74	-2.56
23	363.0	360.41	-2.59	23	362.5	360.41	-2.09
24	378.2	376.08	-2.12	24	378.0	376.08	-1.92
25	394.0	391.75	-2.25	25	394.5	391.75	-2.75
		Mean error	-2.10			Mean error	-2.07

In the lower half of the scale, applicable to depths as great as 20 feet, the error in the newer balance with a single exception is within 0.79 inch and in the average of 20 measurements usual in a snow-course the error will probably approximate the mean error of 0.36 inch. In the upper half of the scale, for snow 20 to 30 feet deep, the error quickly mounts to two inches, the mean error being -2.10 inches. However, so consistent is the error that a reasonable correction-factor could be applied.

The cylindrical balance in the few tests given it appeared to be no more accurate than the dial-type. It suffers also from friction of its closely fitted telescoping parts, so that the index fails to return to the same point with the same load unless tapped or shaken. However, this deviation rarely exceeds one inch. Under heavy load, whereby the frictional area is reduced, the deviation is slight. The use of brass in place of duralumin might correct the error because of its lesser friction.

The range of the cylindrical balance also is limited despite the fact that it has approximately the length of the dial-balance. For example, the balance of "105-inch capacity" is adapted to weighing ten feet of snow of the normal maximum density of 50 per cent; that of "125-inch capacity" to weighing 12.5 feet. However, entire courses in the Sierras have averaged over 55 per cent, which would indicate that individual measurements were even greater. Therefore, there will be occasions when the maximum capacity of the spring-balance will even be less than the figures above. The ideal spring-balance should have a capacity unquestionably above all maximum conditions that can probably arise.

Because of the value of details, Table 2 is given showing the capacity of each type of cylindrical balance with various lengths of sampler and snow-densities.

Table 2--Capacity of cylindrical balances, United States Bureau of Agricultural Engineering

Length of sampler tube	Weight of empty tube	Remainder left for weighing snow	Length of core measurable at a density of		
			30 o/o	40 o/o	50 o/o
ft	water-inches	water-inches	ft	ft	ft
		(1) Scale of 105-inch capacity[a]			
15	64	41	11.33	8.5	7.75
12.5	48	57	over 12.5	12	9.5
10	32	73	over 10	over 10	Over 10
		(2) Scale of 125-inch capacity[b]			
17.5	81	44	12.25	9.33	7.33
15	65	60	over 15	12.5	10
12.5	49	76	over 12.5	over 12.5	12.5

[a] Capacity with normal maximum density is 10 feet of tubing.

[b] Capacity with normal maximum density is 12.5 feet of tubing.

Greater length of the tube of the spring-balance to provide a wider range seems undesirable, particularly because of the discomfort of reading the scale. Furthermore, the graduations have already been made over-fine in the effort to increase range. On the other hand, the dial-balance provides a wide range with large graduations at a uniform comfortable height for reading.

(b) Adjustment to zero--Adjustment to zero, whatever the length of the sampler, is emotionally valuable where recording under winter-conditions in the field should be cut to the minimum and also saves time in making computations at the office, for the water-content is recorded initially in net water-inches. This is difficult if not impossible with the cylindrical balance, which is already set under tension to attain additional range. In fact, the tension as already set by the Bureau of Agricultural Engineering in its adaptation of the Utah balance requires an initial weight of two sections or five feet of sampler to make the balance active.

The objection that the snow-surveyor may neglect to set his instrument to zero may hold true with any instrument. Such neglect will promptly appear in the records and the required habit of adjusting the instrument will tend to beget carefulness in other operations of snow-surveying.

Frederick Herz and Carl Elges suggest that the tendency of the balance to lose its adjustment while being carried from point to point along the snow-course can be controlled by means of a ratchet on the adjusting wheel (see A of Fig. 4), which can be released during operation of the wheel by pressure of the mittened hand.

(c) Other features--In weight and compactness the cylindrical balance excels the dial, but the total weight of the dial-balance is 2.8 pounds or only two pounds heavier than the other. This weight can be somewhat reduced by making a thinner case, but rigidity, essential under conditions of maximum load, might thereby be sacrificed. Offsetting lightness, however, is the protection afforded the dial-balance against snow and sleet, whereas the cylindrical balance may become clogged or even frozen by moisture congealing on its surface, particularly when it is drawn out in weighing. The first cost of the dial-balance is high as compared with the latter, but efficiency under all conditions must be the standard of choice.

(2) Weighing-staff--The original weighing-staff consisted of a combination ski-pole and staff with removable button, but the snow-surveyors have now become so expert on ski that they prefer the slender bamboo-staffs that can not readily be combined into a staff for the balance. Furthermore, the habit of finding a support at the snow-course or using one of the surveyors in its stead is wasteful of energy. Therefore, Carl Elges and Frederick Herz have devised the following staff (see Fig. 6) of duralumin after the original staff, but in sections capable of being carried inside of the sampler-sections themselves. The swivel-hook at the top can be hung into position or removed by lifting and the broad shoulder of the pin holds it firmly in place, though permitting it to swing in a circle. To guard it from becoming easily lost, it is kept attached to the spring-balance, of which it becomes practically a part. A spring in the end of the hook has been suggested by George Hardman as a more dependable means of holding it in place when on the pin. A swivel in place of the present solid ring of the Mount Rose balance would further extend the flexibility of the hook. He also suggests the use of ash as a more comfortable and durable material than duralumin for the staff, providing there is not much increase in weight.

(3) A non-spring balance--In the effort to increase precision in weighing, a request had long been issued for designs for a springless balance but without tangible results until John C. Stevens, Consulting Engineer and designer of hydrological instruments, presented the following model (see Fig. 7). Though this obviously is unsuited for easy transport and setting up and would become clogged readily in storm, it has furnished the basis for a springless balance set on a tripod for use in weighing evaporation-pans, where limited travel, fair weather, and deliberateness are the accompaniments rather than long travel, with possible rough weather, and insistent haste. This balance (see Fig. 8) will prove a valuable supplement to the other snow-survey apparatus.

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QUESTIONNAIRE AND ANSWERS ON SNOW-SURVEY EQUIPMENT AND METHODS

James E. Jones

The sending out of the questionnaire by the Western Interstate Snow-Survey Conference was decided on at the meeting held in Berkeley, California, June 19 to 21, 1934. The obtaining of a list of possibly interested parties to whom the questions could be mailed took a large part of the last half of that year, the preparation of the questions proceeding at the same time.

In the endeavor to obtain a fair report, 231 copies of the questionnaire were mailed to parties in the western states and 75 replies were received and have been tabulated. The replies indicated a lack of ability to make fair comparisons between equipment, in most cases, due to the party having only used one type.

The desirability of a more general plan of cooperation is shown by the willingness of the local agency to perform the field-work, often leaving the forecasting to some central agency that has assumed charge. This may have to be broadened in cases when the local agency desires the immediate use of the data, but this detail can be worked out.

Experimental work appears to be usually performed by universities or similar non-industrial agencies, and would indicate that improvement in equipment and methods can be expected largely from such agencies as have this character of work as one of their reasons for existence.

Of the 75 replies to the questionnaire, 35 expressed interest in a general way but gave no direct response to the questions asked. The questions are given in order to turn attention to essential details, but owing to the wide variety of answers only the general trend of the replies is given.

Question I on equipment--What is your preference as to type, style, material or design, and why, in the following snow-survey equipment? (a) Scales; (b) sample-tube; (c) cutter; (d) coupling; (e) carrying-case for tubes; (f) accessory small tools; (g) ski; (h) ski-poles; (j) ski-wax; (k) ski-accessories; (l) combined ski-and-weighing pole; (m) snow-shoes; (n) snow-shoe accessories; (o) weighing-sling; (p) clothing; (q) equipment-maintenance; (r) new or unusual equipment not of common knowledge; (s) shelter-house location and cost-limits; (t) shelter-house design and equipment; (w) recording snow-gages, dependence, cost, etc.

Answers to Question I--The maximum number of answers (35) was received to Question I and are summarized as follows:

(a) The use of any type-scale appears to be due to the location of the observer, rather than a matter of having made a definite selection because of any real superior points; in other words, they appear to have followed the local custom.

(b) The use of any type of tube appears to be due to the location of the observer. Only two cases reported having changed; all want a light, stainless material.

(c) Mount Rose cutter predominates, but should be less brittle.

(d) Mount Rose coupling is almost exclusively used, probably because of the depth of snow in the Sierras.

(e) Eight do not use carrying-cases for tubes; eight use carrying-cases for tubes; one states that carrying-cases are undesired extra weight; four store the equipment at the course; one states that lack of carrying-case is hard on the horse. Types of carrying-cases are: Three-foot canvas case bound in leather with shoulder-straps for ease of carrying; packboard with pockets for tubes; canvas-bags where tubes are in sections; knapsack-type of carrying-case of canvas with a division for each section of tubing.

(f) Driving-wrenches and cleaning-hooks are used, but by very few.

(g) Ski preferred where the going is not too rough; four have a positive preference for snow-shoes.

(h) Answers scattered; six prefer regulation cane-poles with fiber-rings and leather-webs.

(j) Ski-waxes many and subject to individual preferences.

(k) The wax-boosters agree that proper wax will largely do away with climbing accessories.

(l) Little consistency; seven used a combined weighing-and-ski pole; five either do not use the combined pole or see very little reason for its use; two use a throng around the observer's neck to suspend the scale during weighing; one picks up a pole on the job for use as a weighing-pole.

(m) Snow-shoes appear preferable in very steep, rough country and are safer for men with limited experience.

(n) For snow-shoe accessories the most important appears to be extra strings to repair web.

(o) Practically no suggestion as to improvement or use.

(p) Clothing should be light, but warm, giving freedom of action and is largely a matter of individual taste. Six carry two pairs of gloves or mittens; one uses lined gloves; six prefer arctics, overshoes, or rubber boots; four use ordinary shoes or lace boots; three use ski-boots; dark-glasses are regarded as essential; sweaters or leather-jackets regarded as necessary for warmth during rest-periods or as protection from wind; material used in clothing may be melton-cloth, ordinary wool, army material, canvas, or a double-cotton thickness; protection for the ears is provided by caps or parka-hoods in three cases.

(q) Maintenance-work is done largely after sampling-season. Ski should be kept in racks to maintain curve with inch-block in center, stored in a cool place; ski should be oiled, and oil soaked in--using pine-tar or linseed-oil is the preference of two; tubes are to be shellacked inside and out, using oil on threads to keep them clean; all dents to be taken out of tubes; ski must be trued up and put in good shape before storing; snow-shoes to be fully repaired, shellacked, and put in shape for use before storing away; scales to be calibrated; all small tools put in shape for use before storing; some do the maintenance-work once a year at the time of stocking cabins, others regard it as a matter of constant performance; cutters, or other breakable parts, should have several in stock.

(r) Only seven replied: One thinks all equipment should be standardized; one recommends a kodak, barometer, Brunton transit; one uses a plain mask instead of goggles to prevent snow-blindness; one party believes that the Swiss type spike-creepers would be of advantage on the steep, icy slopes; one party cleans tubes by boiling in "oakite" and varnishing inside with ramrod and swab--bamboo ski-poles filled with linseed-oil to prevent cracking, before storing for summer.

(s) Fourteen replied giving varied experience and recommendations: One recommends shelter-houses 8 by 10 feet and about eight miles apart to be built where danger from snow-slide is least and to be strong enough to resist breaking into by animals; seven parties use existing houses, such as ranger-cabins, old bunk-houses, ranch-houses, and similar places; one party built two shelter-cabins costing $100 each; one party estimates cost of shelter-cabin at $100; two parties estimate cost of cabin at $500; one party recommends an A-shaped structure costing $200--have rat- and mice-proof as far as possible; one party for two or three men wants a building 16 by 20 feet of galvanized iron to be ceiled and to have two windows; one party for two men wants cabin 10 by 12 feet inside and estimates cost at $350; one party recommends cabin 12 by 16 feet built of logs. In deep-snow areas a steep roof is desired; roofing lined with paper under shakes or other material.

(t) Shelter-houses should be equipped with food, bedding, firewood, light, first-aid kit, and cooking equipment; bunks or beds provided; doors and windows covered by shutters of metal; galvanized cans or lined bins provided for storage of food and supplies; in deep-snow areas a "Santa Claus" chimney or door in gable should be provided; provisions should be stored so as to prevent freezing as much as possible; one man gives the cabin-equipment as one double-bed with mattress and bedding, cooking utensils, Coleman lantern with extra mantles and generators, one gallon gasoline, one water-bucket, one wash-basin, and cautions to be sure and check up each year that all is on hand; in place of double-bed, cots may be preferable; a saw and axe, shovel, and thermometer also are needed for safety and information; keep cabin and bins locked.

(w) Experience with recording snow-gages has not been encouraging to date; snow-bridging appears to be the most common difficulty; where electric energy is available, resistance-coils help.

Question II on snow-courses--In the choice of location of snow-courses what points should govern as to the following? (a) Accessibility in relation to usefulness, time required, expense, etc.; (b) terrain including slope, aspect, topographic location, elevations, forest-cover, etc.; (c) number of courses per unit-area of watershed; (d) number and spacing of stations per course; (e) methods of marking courses including design, visibility, and permanence; (f) limits of use to party paying for survey--can course be justified if outside of watershed in which financial agent is otherwise interested?

Answers to Question II numbered in maximum 26 and are summarized as follows:

(a) The question of expense appears to limit the location of the course in the case of those who only allow one day. The general opinion is that the courses should be located in the heart of the watershed, midway between the crest and average lower continuous snow-line. The maximum time-limit appears to be three days.

(b) Snow-courses should be located with consideration to altitudes of basins being surveyed, endeavoring to select representative sections of the watershed that will give good averages of slope, topography, and forest-cover. In some regions it is essential to have courses at several elevations in the watersheds. In some areas open parks are used while others prefer stream-channels; still others mix the features enumerated in the endeavor to get an average. All agree in avoiding sliding and drifting sections, having the course as level as possible and still a good average, and in not avoiding forest-cover entirely.

(c) One believes that one course is sufficient for each watershed or for 50 to 100 square miles; one states that the number of courses depends on the length and variation in elevation of the basin; one believes that courses can be from one to 20 miles apart; others limit the number by variations in elevation-zones, forest-cover, topography, precipitation-characteristics, or occasionally will introduce a second course for checking purposes.

(d) Eleven prefer, or use, a spacing of 100 feet; one prefers, or uses, a spacing of 75 feet; eight prefer, or use, a spacing of 50 feet; one uses a variable of "40 to 50 feet apart"; one states "On long courses space the stations widely, on short ones closely; the length of the courses can depend on the variation in water-equivalent--the closer the agreement the shorter the course"; one states "Depends entirely on exposure to wind--ordinarily 20 to 40 stations 50 feet apart.

(e) Little uniformity, but there must be visibility from one marker to the next. Metal signs preferred--on trees if available. Contrasting, vivid colors, such as black on yellow background or yellow and red.

(f) Three do not justify the cost of survey outside of drainage-area where party paying for same is not interested; nine justify snow-courses outside of the drainage-area where party paying for the same is not interested with the following comments: (1) Snow-survey is an index rather than quantitative measurement, (2) if watershed is in wind-shadow of wind, driftage of basin, (3) if course is representative of conditions in watershed interested, (4) if near divide and found to have relationship to other basin, (5) value in determination of relationship of snowfall on that watershed to watershed in question and general direction of storms, and (6) value for prediction of spring- and summer-runoff and magnitude of potential flow-possibilities in case of warm spring-rain. Parties operating on a budget dependent on earned revenues confine their activities to the watersheds in which they are otherwise interested.

Question III on forecasting--Use of current data, as obtained in past, to forecast runoff? (a) Should reliance be placed upon one system only or should as many methods be used as are known and a mean or other value be used in the final estimate; (b) what is your favorite system; (c) what month is the latest date that should be used in your territory, and to what period is it most applicable; (d) have you developed any correction-factors for (1) precipitation during runoff, (2) soil-absorption, (3) influence of character of preceding year or series of years, (4) abnormal temperatures during runoff-period, and (5) effect of wind on snow-fields; (e) do you use a zoning system; (f) how may the combined snow- and rainfall-data be best utilized in forecasting runoff at the gaging-station at lower end of drainage-basin; (g) how do you calculate normals and how often should they be revised?

Answers to Question III--The maximum number of answers received was 18 and are summarized as follows:

(a) Eleven wish to use as many systems, or methods, as they know; none appears fully satisfied that any system is complete for all cases.

(b) One-half of the replies favor the percentage-system, based on the idea of the average being 100 per cent.

(c) The latest month that should be used to make surveys in local territory was found to be: Five for March; thirteen for April; two for May. There was no definite limit as to territory for any of the three groups. The period to which the results apply appear to include May, June, and July, and in some cases are taken as being good until October.

(d) Development of correction-factors for the five items listed are yet to be made in most cases. Notes on runoff from rain needed; moisture-content of soil should be taken for at least 18 inches; read ground-water elevation in wells; studies of soil-absorption are under way; limited observation of ground-water; necessary in special cases only. Runoff will be less following dry years; static of ground-water of importance; in special cases a marked relation. When snow gets to a density of 40 or 45 per cent it starts to run; abnormal temperatures affect period of runoff; little effect except in speeding or retarding runoff.

(e) Five use zoning-systems; one elevation zone-map is being prepared.

(f) Only the following suggestions were offered: In pumice area rainfall is practically same as snowfall in computing future runoff; combined rain- and snow-records may be used by having general average for several stations for several months ending March 31; get all possible records, group according to similarity of conditions--regrouping will be necessary for each factor considered; snow measurable on ground, but future rain is hard to guess.

(g) Answers various as follows: Two consider normal seven or eight years and recompute every five years until 33-year record is obtained; four revise normal every year, 20 years required for stable normal; one revises normal every ten years; three calculate normal by securing average of ten years, normal average three to five years revised every five years, and prefer parallel normals, that is, same length; two establish normal from available records of snow-cover and extend by comparison with long-time runoff-records, revised each year; one has no normal, due to infancy of record.

Question IV on collateral data--Use of collateral meteorological data? (a) What records are useful; (b) value of data obtained by recording instruments left unattended for relatively long periods of time; (c) value of data obtained at stations remote from snow-courses, but where observers are stationed; (d) value of thermograph- and temperature-records with or without accompanying precipitation-observations; (e) value of master-stations, with observers, at crest-line, or other points to obtain records at present not available due to altitude or remoteness from habitation, these "master-stations" to be operated by some control-agency similar to Weather Bureau. [The master-station question is intended to get the opinion as to the desirability of experimental stations of a grade comparable to the standard Weather Bureau station. These stations would be operated by a general agency for experimental work primarily, the routine data being incidental to tie in with the regular work of the local snow-surveys.]

Answers to Question IV were received in maximum number of eleven and are summarized as follows:

(a) All agree that precipitation-records are essential. Eight include temperature as being at least useful; one states that more mountain-data on precipitation, temperature, wind-velocity, and other meteorological items are needed, because the Weather Bureau stations are not in mountain-sections where greatest variations occur. Others believe that "every record obtained is just so much added to knowledge of conditions." Use of runoff-records, ground-water storage, soil-absorption studies, evaporation, and wind-movement are each given consideration by one or more respondents.

(b) The general opinion is that with present instruments the results are not satisfactory. One says that they are better than nothing; one requires special equipment set in picked locations; one has found rain-records satisfactory, but is doubtful as to snow.

(c) The value is dependent on the relationship of the observed station-conditions to those of the snow-area. Six believe they are of value in showing the general trend and enable the forecaster to back up his judgment with data not otherwise available; one has observations made at power-houses that are not too far removed from the snow-area and finds them of great value; one gives weight to the human element in making observations, and believes the records of value if the observer is trustworthy; one finds them of no value.

(d) Their value appears to be limited to the melting season and as additional data for study.

(e) Seven believe that the master-station would yield valuable data, either in developing the theoretical angles or possibly in practical uses if properly located; one believes it not desirable; one already has a station that is being used to some degree in this manner and has found it very useful.

Question V on stream-flow data--Use of stream-flow data? (a) Does extension of normals by use of precipitation-data give results that are as valuable as extension by comparison with another stream to a short record of runoff; (b) is channel-seepage a factor that varies enough to affect the estimate of future runoff; (c) is soil-absorption from the snow-field a factor well enough known at present for mathematical use; (d) is the effect of a series of either wet or dry years upon runoff possible of reduction to a mathematical factor?

Answers to Question V were received in maximum number of 18 and may be summarized thus:

(a) Eight have a decided preference for the extension of normals by the use of runoff-records; one believes that precipitation-records give the more valuable results in extension of normals as runoff-records include too many local abnormalities; one desires to use both methods and to follow a mean; one believes that parallel normals between streams are perhaps best, providing one is unusually long.

(b) The general opinion appears to be that to effect the estimate the station being used for runoff-data, if in a mountain-area, will not be greatly affected but, if in alluvial plain, may show a marked effect.

(c) Sixteen agree that not enough is known about this subject to use it as a factor; one states that if no frost is in the ground it is estimated that one-half of the snowfall will go into the ground; soil-absorption is an important factor in determining the yield from the snow-field, especially in those years when the cover is less than 70 per cent of normal; one states that soil-absorption varies too much in individual areas to be reduced to an arbitrary formula.

(d) Five believe that with a record of some length it will be possible to show the effect of a series of wet or dry years in a mathematical, or graphical, manner so as to use it as a factor; five do not believe it possible; two believe it depends on the geological and topographic conditions.

Question VI on cost of snow-surveys--Cost of snow-surveys? (a) Preliminary surveys or routine surveys; (b) are costs cooperative expenses or are they paid by one party in your territory; (c) what are the prevailing rates of pay for observers; (d) how are transportation-costs paid; (e) how many observers make up a party and do they comprise entire party--if others, who are they?

Answers to Question VI numbered in maximum 25 and are summarized below:

(a) Regarding preliminary surveys one replied that cost of preliminary surveys and establishment of snow-courses had been about $25 per course; one states that it is volunteer-work; one says costs are traveling expense only and not serious. Regarding routine surveys one states routine costs are $50 per course annually; one gives routine costs in one area as $10 per course and in another area as $15; one states that cost depends on wage-rates, and that he pays a $5 bonus in one area and also that in Sierra Nevadas a bonus of from $1 to $15 is paid and that not less than two make a party; one states that routine survey costs about $10; one estimates costs of salary and mileage of routine surveys at $12.38 per two-man party per day.

(b) Fourteen have cooperation in payment of expense and nine pay the bill through one agency. Forest-service men on regular pay do the field-work in seven cases that replied, the office-work and equipment being furnished by other agencies. In one case the party paid all current expenses, but the equipment was furnished; one man carried on snow-studies personally while on other survey-work for State.

(c) One makes the statement that snow-surveyors "should be well paid and also insured"; one had a pay of $3.50 per day for the helper plus $1 per day each for two horses; three have a pay of $4 per day; two have a pay-scale of $4 to $5 per day; one had a pay of $4.50 per day; four pay $5 per day; two pay $6 per day; one has a pay of $7 per day; one has a pay of $7.50 per day; one has a pay of $8.75 per day for observers; one has a salary-rate of $10 per day plus subsistence; one is paid $15 per day and expenses; one has no pay, the work being voluntary. In one case of the $4 to $5 class it is for the man and horse with no travel-expense allowed; in the second case of the $4 to $5 class it is for the helper. In six cases the replies indicate the use of regular employees and the pay is their usual salary, the snow-survey being a part of the work that they are hired to do during the year.

(d) Six have no transportation-bills or else the pay given the man includes his transportation; four pay transportation on a mileage-basis; three pay transportation from a cooperative fund, but do not state manner; one pays the "actual expense"; one states that formerly he had cooperation with the State but that present program is curtailed due to lack of State funds.

(e) Eighteen prefer two to a party; five desire three to a party; one reply indicates the possible use on occasion of only one man. Visitors often are taken along for the experience.

Department of Water and Power of the City of Los Angeles,
Los Angeles, California

HISTORICAL AND ADMINISTRATIVE

J. E. Church

Two sessions of the Western Interstate Snow-Survey Conference were held during the year ending May 31, 1936.

One of an informal nature was held at Salt Lake City, November 16, 1935, in connection with the National Reclamation Association to discuss snow-survey methods and Federal cooperative plans with Montrose W. Hayes, Chief, River and Flood Division of the United States Weather Bureau. Some 20 representatives of Federal bureaus and irrigation-projects were present.

The second session was held at the California Institute of Technology at Pasadena, California, January 31, 1936, in affiliation with the West Coast Meeting of the Section of Hydrology of the American Geophysical Union. The registered attendance at this session was 88. The attendance at the dinner-business session was 33.

To keep pace with the widened area of snow-surveying made possible by the recent organization of the Federal-State Cooperative Snow-Survey, the number of members of the Executive Committee was greatly increased, that Committee as now appointed for 1936-37 including the following:

Professor George D. Clyde, Director of Utah Cooperative Snow-Surveys, Utah Agricultural Experiment Station, Logan, Utah, Chairman
Harlowe M. Stafford, Snow-Supervisor, California Cooperative Snow-Surveys, Sacramento, California
James E. Jones, Assistant Engineer, Los Angeles Department of Water and Power, Los Angeles, California
Professor H. P. Boardman, Chairman of Forecast Committee of Nevada Cooperative Snow-Surveys, University of Nevada, Reno, Nevada
R. A. Work, Assistant Irrigation-Engineer, United States Division of Irrigation, Medford, Oregon
James C. Marr, Associate Irrigation-Engineer, United States Division of Irrigation, Boise, Idaho
R. L. Parshall, Senior Irrigation-Engineer, United States Division of Irrigation, Colorado Agricultural Experiment Station, Fort Collins, Colorado
W. A. Lamb, District Engineer, United States Geological Survey (Water-Resources Branch), Helena, Montana
Lynn Crandall, District Engineer, United States Geological Survey and Water-Master District No. 36, Idaho Falls, Idaho
J. Cecil Alter, Meteorologist, United States Weather Bureau, Salt Lake City, Utah
Professor Joseph Kittredge, Jr., Department of Forestry, University of California, Berkeley, California

The Executive Committee was requested to assist the American Geophysical Union financially in the publication of Conference papers.

University of Nevada,
Reno, Nevada

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